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<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2017-10-01
		Page:	3 of <a href="#">132</a>

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<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2017-10-01
		Page:	5 of 132

## Contents

<b>1</b>	<b>Introduction</b>	<b>11</b>
1.1	Purpose . . . . .	11
1.2	Acknowledgements . . . . .	11
1.3	Scope and references . . . . .	11
1.4	Reference and applicable documents . . . . .	11
<b>2</b>	<b>Overview</b>	<b>14</b>
<b>3</b>	<b>EFOSC2 instrument description</b>	<b>15</b>
3.1	Instrumentoverview . . . . .	15
<b>4</b>	<b>Quick start</b>	<b>16</b>
4.1	An introductionto Gasgano and Esorex . . . . .	16
4.1.1	Using Gasgano . . . . .	16
4.1.2	Using Esorex . . . . .	20
4.2	Example of imaging data reduction using Esorex . . . . .	22
4.3	Example of MOS data reduction using Esorex . . . . .	26
4.4	Example of long-slit data reduction using Esorex . . . . .	30
<b>5</b>	<b>Known Problems</b>	<b>34</b>
<b>6</b>	<b>Instrument Data Description</b>	<b>35</b>
6.1	General frames . . . . .	35
6.2	IMG frames . . . . .	36
6.3	MOS frames . . . . .	37
<b>7</b>	<b>Static Calibration Data</b>	<b>40</b>
7.1	Photometric table . . . . .	40
7.2	Photometric standard stars catalog . . . . .	41
7.3	Grism table . . . . .	43
7.4	Arc lamp lines catalog . . . . .	43
7.5	Global distortion table . . . . .	44

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.0
		Date:	Date 2017-10-01
		Page:	6 of 132

7.6	Atmospheric extinction table . . . . .	45
7.7	Standard star flux table . . . . .	45
<b>8</b>	<b>Data Reduction</b>	<b>47</b>
8.1	Imaging data reduction overview . . . . .	47
8.1.1	Required input data . . . . .	47
8.1.2	Reduction cascade . . . . .	49
8.2	Spectral data reduction overview . . . . .	49
8.2.1	Required input data . . . . .	49
<b>9</b>	<b>Pipeline Recipes Interfaces</b>	<b>52</b>
9.1	efosc_bias . . . . .	52
9.1.1	Input files . . . . .	52
9.1.2	Output files . . . . .	52
9.1.3	Configuration parameters . . . . .	52
9.1.4	Quality control parameters. . . . .	53
9.2	efosc_img_screen_flat . . . . .	54
9.2.1	Input files . . . . .	54
9.2.2	Output files . . . . .	54
9.2.3	Configuration parameters . . . . .	54
9.2.4	Quality control parameters. . . . .	55
9.3	efosc_img_sky_flat . . . . .	56
9.3.1	Input files . . . . .	56
9.3.2	Output files . . . . .	56
9.3.3	Configuration parameters . . . . .	56
9.3.4	Quality control parameters. . . . .	57
9.4	efosc_img_science . . . . .	57
9.4.1	Input files . . . . .	57
9.4.2	Output files . . . . .	57
9.4.3	Configuration parameters . . . . .	58
9.4.4	Quality control parameters. . . . .	59

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2017-10-01
		Page:	7 of 132

9.5	efosc_zeropoint . . . . .	60
9.5.1	Input files . . . . .	62
9.5.2	Output files . . . . .	62
9.5.3	Configuration parameters . . . . .	63
9.5.4	Quality control parameters. . . . .	65
9.6	efosc_photometry . . . . .	65
9.6.1	Input files . . . . .	67
9.6.2	Output files . . . . .	68
9.6.3	Configuration parameters . . . . .	69
9.6.4	Quality control parameters. . . . .	69
9.7	efosc_calib . . . . .	70
9.7.1	Input files . . . . .	70
9.7.2	Output files . . . . .	71
9.7.3	Configuration parameters . . . . .	80
9.7.4	Quality control parameters. . . . .	85
9.8	efosc_science . . . . .	86
9.8.1	Input files . . . . .	87
9.8.2	Output files . . . . .	89
9.8.3	Configuration parameters . . . . .	93
9.8.4	Quality control parameters. . . . .	98
9.9	efosc_extract . . . . .	98
<b>10</b>	<b>Algorithms</b>	<b>99</b>
10.1	Propagation of photonic and readout noise . . . . .	99
10.2	Frame zeropoint computation . . . . .	100
10.2.1	Error propagation in a nutshell . . . . .	100
10.2.2	Optimally weighted average . . . . .	103
10.3	The efosc_photometry recipe . . . . .	106
10.4	Determination of spectral response and efficiency curves . . . . .	108
10.5	Spectrophotometric calibration . . . . .	109
10.6	Overview of the spectral self-calibration procedure . . . . .	109

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2017-10-01
		Page:	8 of 132

10.6.1	1D peak-detection . . . . .	110
10.6.2	1D pattern-recognition . . . . .	112
10.6.3	Determination of the spectral range . . . . .	115
10.6.4	Choice of a reference wavelength . . . . .	115
10.6.5	Position of the reference wavelength on the CCD . . . . .	115
10.6.6	2D pattern-recognition . . . . .	116
10.6.7	Optical distortion model determination . . . . .	118
10.6.8	Tracing slit spectra edges . . . . .	118
10.6.9	Spatial curvature model determination . . . . .	119
10.6.10	Extraction of slit spectra . . . . .	119
10.6.11	Alignment of the extraction mask to the scientific spectra . . . . .	119
<b>A</b>	<b>Troubleshooting Guide</b>	<b>120</b>
A.1	Checking the results of recipe efosc_calib . . . . .	120
A.1.1	Were all spectra detected and properly traced? . . . . .	120
A.1.2	Were all spectra properly calibrated in wavelength? . . . . .	120
A.1.3	Is the spectral resolution as expected? . . . . .	121
A.2	Fixing pattern-recognition failures in efosc_calib . . . . .	122
A.2.1	Some arc lamp reference lines are missing . . . . .	122
A.2.2	Some arc lamp reference lines are very faint . . . . .	123
A.2.3	The reference lines in the arc lamp exposure are very broad . . . . .	123
A.2.4	The spectral dispersion is not what expected . . . . .	123
A.2.5	There are spectra at very large offsets . . . . .	123
A.3	Fixing other possible failures in efosc_calib . . . . .	123
A.3.1	The spectra are too tightly packed . . . . .	124
A.3.2	The wavelength calibration residuals display systematic trends . . . . .	124
A.3.3	The calibrated spectra look "noisy" at their ends . . . . .	124
A.3.4	The calibrated long-slit spectrum looks distorted . . . . .	124
A.3.5	The flat field is not properly normalised . . . . .	125
A.3.6	Valid reference lines are rejected . . . . .	125
A.4	Checking the results of recipes efosc_science . . . . .	125



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	9 of 132

A.4.1	Were all spectra properly wavelength calibrated? . . . . .	125
A.4.2	Is the sky background properly subtracted? . . . . .	127
A.4.3	Were all objects detected? . . . . .	128
A.4.4	Were all the detected objects properly extracted? . . . . .	128
A.5	Fixing failures in efosc_science . . . . .	128
A.5.1	The wavelength calibration is bad . . . . .	128
A.5.2	The sky alignment of the wavelength solution failed . . . . .	129
A.5.3	The sky subtraction failed for resolved sources . . . . .	129
A.5.4	The sky subtraction failed for curved or tilted slits . . . . .	129
A.5.5	Cosmic rays are not removed . . . . .	129
A.5.6	The sampling of the remapped scientific spectra is poor . . . . .	130
A.5.7	The extracted spectra are normalised in time . . . . .	130
A.5.8	There are often spurious objects detected at the slit edges . . . . .	130
A.5.9	Some "obvious" objects are not detected . . . . .	130
<b>B</b>	<b>Installation</b>	<b>131</b>
<b>C</b>	<b>Abbreviations and acronyms</b>	<b>132</b>

<b>ESO</b>	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	10 of <a href="#">132</a>

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	11 of 132

# 1 Introduction

## 1.1 Purpose

The EFOSC pipeline is a subsystem of the *VLT Data Flow System* (DFS). It is used by the *La Silla Site Operations* (LSO), in the quick-look assessment of data, in the generation of master calibration data, in the reduction of scientific exposures, and in the data quality control. Additionally, the EFOSC pipeline recipes are made public to the user community to enable a more personalised processing of the data from the instrument.

This manual is a complete description of the imaging and spectroscopic data reduction recipes reflecting the status of the EFOSC pipeline as of 01.10.2017 (version 2.3.0).

## 1.2 Acknowledgements

The EFOSC pipeline is essentially a clone of the FORS pipeline [13], and as such it is based on the CPL [1] developed by the ESO/SDD/PSD.

Ivo Saviane (ESO La Silla Paranal Observatory) extensively tested the data reduction procedures by carefully examining their products. His patient work and great insight have been vital to this project.

## 1.3 Scope and references

This document describes the EFOSC pipeline.

Updated versions of the present document may be found on [18].

Additional information on the Common Pipeline Library (CPL), *Esorex* and *Gasgano* can be found at [1], [2], [12], [14], and [15]. A description of the instrument is in [6]. The EFOSC user manuals [17], [16], and [10], can be found in <http://www.eso.org/instruments/efosc/doc/>.

## 1.4 Reference and applicable documents

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	12 of 132

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- [3] *Deliverables Specification*. VLT-SPE-ESO-19000-1618.
- [4] *DFS Pipeline & Quality Control – User Manual*. VLT-MAN-ESO-19500-1619.
- [5] *EFOSC Calibration Plan*. [6]/doc/efosc2\_calplan.html. 45
- [6] *EFOSC instrument home page*. <http://www.eso.org/sci/facilities/lasilla/instruments/efosc/>. 11, 12
- [7] *EFOSC2 Instruments Description*. <http://www.eso.org/sci/facilities/lasilla/instruments/efosc/inst/>. 15
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<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	13 of 132

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- [29] W. H. Press et al. *Numerical Recipes in C*. Second Edition (1992). [107](#)

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	14 of 132

## 2 Overview

In collaboration with instrument consortia, the Data Flow Systems Department (DFS) of the Data Management and Operation Division is implementing data reduction pipelines for the most commonly used VLT/VLTI instrument modes. These data reduction pipelines have the following three main purposes:

**Data quality control:** pipelines are used to produce the quantitative information necessary to monitor instrument performance.

**Master calibration product creation:** pipelines are used to produce master calibration products (e.g., combined bias frames, super-flats, wavelength dispersion solutions).

**Science product creation:** using pipeline-generated master calibration products, science products are produced for the supported instrument modes (e.g., optimally extracted spectra, bias-corrected and flat-fielded images, wavelength-calibrated spectra). The accuracy of the science products is limited by the quality of the available master calibration products and by the algorithmic implementation of the pipelines themselves. In particular, adopted automatic reduction strategies may not be suitable or optimal for all scientific goals.

Instrument pipelines consist of a set of data processing modules that can be called from opportune front-end applications, such as the automatic data management tools available on Paranal.

ESO offers two front-end applications for launching pipeline recipes, *Gasgano* [15] and *Esorex* [12], both included in the pipeline distribution. These applications can also be downloaded separately from the ESO web pages (see [14] and [12]). An illustrated introduction to *Gasgano* is provided in the "Quick Start" Section of this manual (see page 16).

The EFOSC2 instrument and the different types of raw frames and auxiliary data are described in Sections 3, 6, and 7.

A brief introduction to the usage of the available reduction recipes using *Gasgano* or *Esorex* is presented in Section 4, and in Section 5 known data reduction problems are listed, providing also possible solutions; but it is strongly suggested to read also the Troubleshooting Guide in the Appendix (page 120), which goes even deeper into that.

More details on what are inputs, products, quality control measured quantities, and controlling parameters of each recipe are given in Section 9.

More detailed descriptions of the data reduction algorithms used by the individual pipeline recipes can be found in Section 10.

In Appendix C a list of used abbreviations and acronyms is given.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	15 of <a href="#">132</a>

### 3 EFOSC2 instrument description

EFOSC2 (ESO Faint Object Spectrograph and Camera, v.2) was originally built at La Silla as the first light instrument for the NTT, in 1989, before EMMI (the ESO Multi-Mode Instrument) was ready. It was based on the reliable and versatile original EFOSC1, but with a few improvements. With the arrival of EMMI, EFOSC2 moved to the 2.2m, and then to the 3.6m from period 60 (December 1997) as EFOSC1 was decommissioned.

EFOSC2 was transferred back to the NTT at the start of period 81 (April 2008), replacing EMMI.

Only a brief description of the instrument is given here. For more details please refer to [7] and [9].

#### 3.1 Instruments overview

EFOSC2 is a very versatile instrument for low resolution spectroscopy and imaging. The instrument has multi mode capability including normal/polarimetric imaging/spectroscopy (several submodes in each), multi-object spectroscopy and coronagraphy.

The real forte of EFOSC2 is low resolution spectroscopy, given its high efficiency in terms of both photons and time. A second feature of this instrument is its sensitivity to UV photons.

EFOSC2 is a focal reducer using multi-layer coated all-transmission optics. The wavelength range of operation is between 3050 Å and 11000 Å. The field of view is 4.1'x4.1'.

The CCD is a Loral/Lesser, thinned, AR coated, UV flooded, MPP chip controlled by ESO-FIERA. It's size is 2048 x 2048 pixel, the pixel size being 15x15  $\mu$ , or 0.12"x0.12" on the sky. The default CCD readout modes are 2x2 binned pixels.

Please find more detail in [8].

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	16 of 132

## 4 Quick start

This section describes the most immediate usage of the EFOSC pipeline recipes. For a complete list of the available recipes, please see Section 8, page 47.

### 4.1 An introduction to Gasgano and Esorex

Before being able to apply pipeline recipes to a set of data, the data must be opportunely classified, and associated with the appropriate calibrations. The *Data Classification* consists of tasks such as: "What kind of data am I?", e.g., BIAS, "To which group do I belong?", e.g., to a particular Observation Block or template. *Data Association* is the process of selecting appropriate calibration data for the reduction of a set of raw science frames. Typically, a set of frames can be associated if they share a number of properties, such as instrument and detector configuration. As all the required information is stored in the FITS headers, data association is based on a set of keywords (called "association keywords") and is specific to each type of calibration.

The process of data classification and association is known as data organisation. The *DO Category* is the label assigned to a data type as a result of data classification.

An instrument pipeline consists of a set of data processing modules that can be called from different host applications, either from the command line with *Esorex* [12], from the automatic data management tools available at Paranal and La Silla, or from the graphical *Gasgano* tool [14].

*Gasgano* is a data management tool that simplifies the data organisation process, offering automatic data classification and making the data association easier (*even if automatic association of frames is not yet provided*). *Gasgano* determines the classification of a file by applying an instrument specific rule, while users must provide this information to the recipes when they are executed manually using *Esorex* from the command line. In addition, *Gasgano* allows the user to execute directly the pipeline recipes on a set of selected files.

#### 4.1.1 Using Gasgano

To get familiar with the EFOSC pipeline recipes and their usage, it is advisable to begin with *Gasgano*, because it provides a complete graphic interface for data browsing, classification and association, and offers several other utilities such as easy access to recipes documentation and preferred data display tools.

*Gasgano* can be started from the system prompt in the following way:

```
gasgano &
```

The *Gasgano* main window will appear. On Figure 4.1.1 (page 17), a view on a set of EFOSC MOS data is shown as an example. *Gasgano* can be pointed to the directories where the data to be handled are located using the navigation panels accessible via the *Add/Remove Files* entry of the *File* menu (shown on the upper left of the figure).

The data are hierarchically organised as preferred by the user. After each file name are typically shown the observation date, the classification, the target of the observation, and the grism/filter combination that was



ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	17 of 132

used.<sup>1</sup>

More information about a single frame can be obtained by clicking on its name: the corresponding FITS file header will be displayed on the bottom panel, where specific keywords can be opportunely filtered and searched. Images and tables may be easily displayed using the viewers specified in the appropriate *Preferences* fields.

Frames can be selected from the main window for being processed by the appropriate recipe: on Figure 4.1.2, a MOS arc lamp exposure with a sequence of flat field exposures, bias frames, a catalog of reference lines, and a configuration table, are all selected and sent to the *efosc\_calib* recipe. This will open a *Gasgano* recipe execution window (see Figure 4.1.3), having all the specified files listed in its *Input Frames* panel.

Help about the recipe may be obtained from the *Help* menu. Before launching the recipe, its configuration may be opportunely modified on the *Parameters* panel (on top). The window contents might be saved for later use by selecting the *Save Current Settings* entry from the *File* menu, as shown in figure.

At this point the recipe can be launched by pressing the *Execute* button. Messages from the running recipe will appear on the *Log Messages* panel at bottom, and in case of successful completion the products will be listed on the *Output Frames* panel, where they can be easily viewed and located back on the *Gasgano* main window.

Please refer to the *Gasgano User's Manual* [15] for a more complete description of the *Gasgano* interface. See also [14].

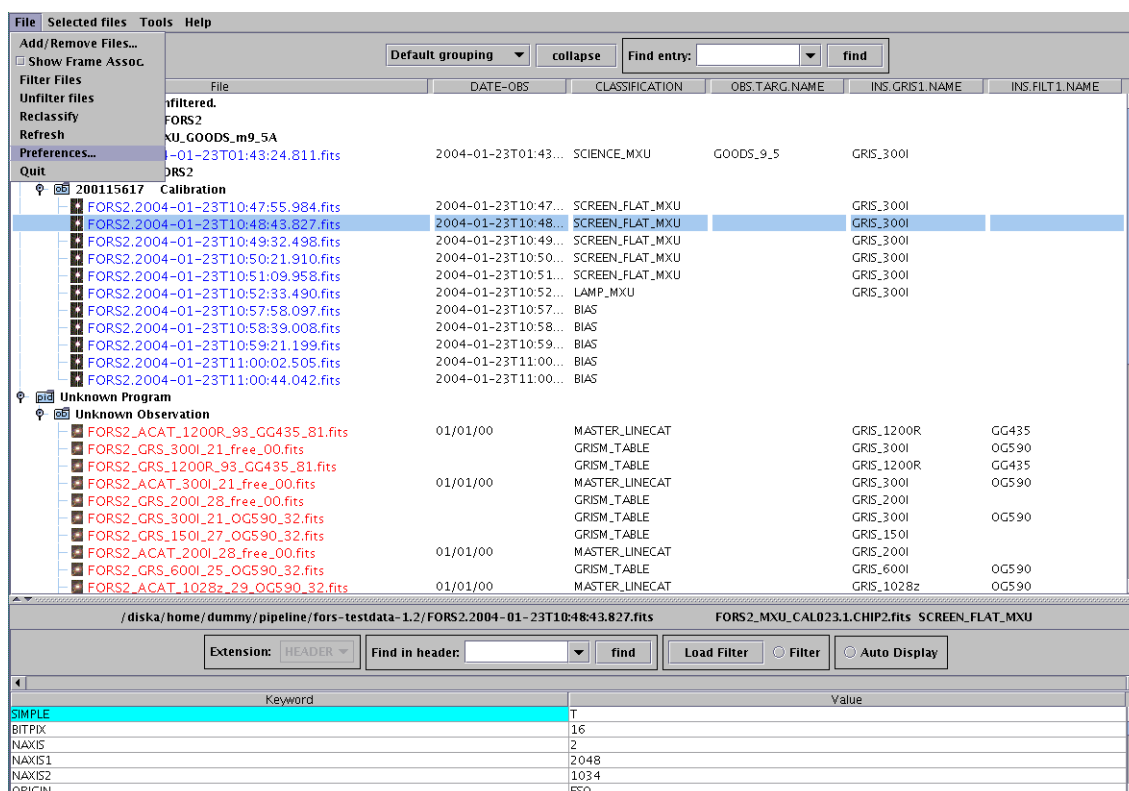


Figure 4.1.1: The *Gasgano* main window.

<sup>1</sup>The user can configure what keywords should be displayed.

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	18 of 132

The screenshot displays the ESO pipeline software interface. At the top, there is a menu bar with 'File', 'Selected files', 'Tools', and 'Help'. Below the menu bar, a toolbar contains buttons for 'Display...', 'To Recipe', 'Load Recipe', 'fors\_calib', 'fors\_science', 'fault grouping', 'collapse', 'Find entry:', and 'find'. A search bar with the number '13' is also present.

The main window shows a list of files and their associated metadata. The files are organized into categories: '200115617 Calibration' and 'Unknown Program'. The 'Unknown Program' category is expanded, showing a list of files with their respective dates, times, and classifications. The files are listed in a table with columns for 'File', 'DATE-OBS', 'CLASSIFICATION', 'OBS.TARG.NAME', 'INS.GRIS1.NAME', and 'INS.FILT1.NAME'.

Below the file list, there is a section for 'Unknown Observation' with a similar table structure. The files are listed with their respective dates, times, and classifications.

At the bottom of the interface, there is a section for 'Keyword' and 'Value' pairs. The keywords listed are 'SIMPLE', 'BITPIX', 'NAXIS', 'NAXIS1', 'NAXIS2', and 'ORIGIN'. The corresponding values are 'T', '16', '2', '2048', '1034', and 'ESO'.

Figure 4.1.2: Selecting files to be processed by a EFOSC pipeline recipe.

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	19 of 132

File Help

Save Current Settings  
Load Current Settings  
Clear Current  
Close

Sealing

me	Value	Default	Range
mos.fors_camo.smcident	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
mos.fors_calib.sdegree	4	4	
mos.fors_calib.ddegree	-1	-1	
mos.fors_calib.dradius	10	10	
mos.fors_calib.sradius	10	10	
mos.fors_calib.qc	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	

Input Frames

Include	Filename	Classification	Locate	Display
<input checked="" type="checkbox"/>	FORS2_2004-01-23T10:58:39.008.fits	BIAS	Locate	Display
<input checked="" type="checkbox"/>	FORS2_2004-01-23T10:59:21.199.fits	BIAS	Locate	Display
<input checked="" type="checkbox"/>	FORS2_2004-01-23T11:00:02.505.fits	BIAS	Locate	Display
<input checked="" type="checkbox"/>	FORS2_2004-01-23T11:00:44.042.fits	BIAS	Locate	Display
<input checked="" type="checkbox"/>	FORS2_GRS_300L_21_free_00.fits	GRISM_TABLE	Locate	Display
<input checked="" type="checkbox"/>	FORS2_ACAT_300L_21_free_00.fits	MASTER_LINECAT	Locate	Display

Product Naming

Product Root Directory: /diska/home/dummy/pipeline/fors-testdata-1.2 Browse Naming Scheme: Numeric

Execute

Output Frames

Filename	Classification	Locate	Display
spectral_resolution_mxu_0000.fits	SPECTRAL_RESOLUTION_MXU	Locate	Display
disp_coeff_mxu_0000.fits	DISP_COEFF_MXU	Locate	Display
global_distortion_table_0000.fits	GLOBAL_DISTORTION_TABLE	Locate	Display
reduced_lamp_mxu_0000.fits	REDUCED_LAMP_MXU	Locate	Display
wavelength_map_mxu_0000.fits	WAVELENGTH_MAP_MXU	Locate	Display
spatial_map_mxu_0000.fits	SPATIAL_MAP_MXU	Locate	Display
curv_coeff_mxu_0000.fits	CURV_COEFF_MXU	Locate	Display
slit_location_mxu_0000.fits	SLIT_LOCATION_MXU	Locate	Display

Log Messages

Save Clear

```

15:40:34 [ INFO ] RMS for 9784.50: 0.110 pixel (706 points)
15:40:34 [ INFO ] RMS for 10830.17: 0.281 pixel (343 points)
15:40:34 [ INFO ] RMS for 10957.30: 0.433 pixel (342 points)
15:40:34 [ INFO ] Mean residual: 0.151128 pixel
15:40:34 [ INFO ] Mean model accuracy: 0.059537 pixel (0.190519 Å)
15:40:34 [ INFO ] Mean spectral resolution: 669.76
15:40:34 [ INFO ] Mean reference lines FWHM: 3.85 +/- 0.09 pixel
15:40:34 [ INFO ] Saving SPECTRAL_RESOLUTION_MXU table to disk...

```

Figure 4.1.3: The Gasgano recipe execution window.

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	20 of 132

#### 4.1.2 Using Esorex

*Esorex* is a commandline utility for running pipeline recipes. It may be embedded by users into data reduction scripts for the automation of processing tasks. On the other side, *Esorex* does not offer all the facilities available with *Gasgano*, and the user must classify and associate the data using the information contained in the FITS header keywords (see Section 6.1, page 35). The user should also take care of defining the input set-of-frames and the appropriate configuration parameters for each recipe run:

**The set-of-frames:** Each pipeline recipe is run on a set of input FITS data files. When using *Esorex* the filenames must be listed together with their DO category in an ASCII file, the *set-of-frames* (SOF), which is required when launching a recipe.<sup>2</sup>

Here is an example of SOF, valid for the *efosc\_calib* recipe:

```
EFOSC.2006-05-10T12:58:27.122.fits SCREEN_FLAT_MOS
EFOSC.2006-05-10T12:59:45.326.fits SCREEN_FLAT_MOS
EFOSC.2006-05-10T13:00:20.930.fits SCREEN_FLAT_MOS
EFOSC.2006-05-10T13:01:17.711.fits SCREEN_FLAT_MOS
EFOSC.2006-05-10T13:02:14.559.fits SCREEN_FLAT_MOS
EFOSC.2006-05-10T13:03:37.926.fits LAMP_MOS
../cal/EFOSC_MBIAS.fits MASTER_BIAS
../cal/EFOSC_ACAT_15.fits LINE_CATALOG
```

This file contains the name of each input frame, and its DO category. The launched pipeline recipe will access the listed files when required by the reduction algorithm.

Note that the EFOSC pipeline recipes do not verify in any way the correctness of the *DO Category* specified by the user in the SOF. The reason of this lack of control is that the EFOSC recipes are just the DRS component of the complete pipeline running on La Silla, where the task of data classification and association is carried out by separate applications. Moreover, using *Gasgano* as an interface to the pipeline recipes will always ensure a correct classification of all the data frames, assigning the appropriate DO category to each one of them (see Section 4.1.1, page 16).

A recipe handling an incorrect SOF may stop or display unclear error messages at best. In the worst cases, the recipe would apparently run without any problem, producing results that may look reasonable, but are actually flawed.

**Esorex syntax:** The basic syntax to use *Esorex* is the following:

```
esorex [esorex_options] recipe_name [recipe_options] set_of_frames
```

To get more information on how to customise *Esorex* (see also [12]) run the commands:

```
esorex -man
esorex -help
esorex -par
```

<sup>2</sup>The set-of-frames corresponds to the *Input Frames* panel of the *Gasgano* recipe execution window (see Figure 4.1.3, page 19).

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	21 of 132

To generate a configuration file `esorex.rc` in the directory `$HOME/.esorex` run the command:

```
esorex -create-config
```

A list of all available recipes, each with a one-line description, can be obtained using the command:

```
esorex -recipes
```

All recipe parameters (aliases) and their default values can be displayed by the command

```
esorex -params recipe_name
```

To get a brief description of each parameter meaning execute the command:

```
esorex -help recipe_name
```

To get more details about the given recipe use the commands:

```
esorex -man recipe_name
esorex -help recipe_name
esorex -par recipe_name
```

**Recipe configuration:** Each pipeline recipe may be assigned an *Esorex* configuration file, containing the default values of the parameters related to that recipe.<sup>3</sup> The configuration files are normally generated in the directory `$HOME/.esorex`, and have the same name as the recipe to which they are related, with the filename extension `.rc`. For instance, the recipe *efosc\_calib* has its *Esorex* default configuration file named `efosc_calib.rc`, generated with the command:

```
esorex -create-config efosc_calib
```

If a number of recipe parameters are specified on the command line, the given values will be used in the created configuration file.

The definition of one parameter in the configuration file may look like this:

```
# --slit_ident
# Attempt slit identification.
efosc.efosc_calib.slit_ident=TRUE
```

---

<sup>3</sup>The *Esorex* recipe configuration file corresponds to the *Parameters* panel of the *Gasgano* recipe execution window (see Figure 4.1.3, page 19).



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	22 of 132

In this example, the parameter `efosc.efosc_calib.slit_ident` is set to the value `TRUE`. In the configuration file generated by *Esorex*, one or more comment lines are added containing information about the possible values of the parameter, and an alias that could be used as a commandline option.

The recipes provided by the EFOSC pipeline are designed to implement a cascade of macro data reduction steps, each controlled by its own parameters. For this reason and to prevent parameter name clashes it is specified as parameter prefix not only the instrument name but also the name of the step they refer to. Shorter parameter aliases are made available for use on the commandline.

A description of the recipe parameters is provided in Section 9, page 52.

**Recipe execution:** A recipe can be run by specifying its name to *Esorex*, together with the name of a set-of-frames. For instance, the following command line would be used to run the recipe *efosc\_calib* for processing the files specified in the set-of-frames `cal.sof`:

```
esorex efosc_calib cal.sof
```

The recipe parameters can be modified either by editing directly the used configuration file, or by specifying new parameter values on the commandline using the commandline options defined for this purpose. Such command line options should be inserted after the recipe name and before the SOF name, and they will supersede the system defaults and/or the configuration file settings. For instance, to set the *efosc\_calib* recipe *slit\_ident* parameter to `false`, the following may be typed:

```
esorex efosc_calib -slit_ident=false cal.sof
```

For more information on *Esorex*, see [12].

## 4.2 Example of imaging data reduction using Esorex

In the following, a typical EFOSC imaging data reduction procedure is described.<sup>4</sup> It is assumed that the following data are available:

One scientific exposure:

```
EFOSC.2007-08-30T23:41:28.745.fits SCIENCE_IMG
```

Four sky field exposures:

```
EFOSC.2007-08-30T23:01:46.059.fits SKY_FLAT_IMG
EFOSC.2007-08-30T23:02:22.453.fits SKY_FLAT_IMG
EFOSC.2007-08-30T23:02:59.897.fits SKY_FLAT_IMG
EFOSC.2007-08-30T23:03:38.441.fits SKY_FLAT_IMG
```

---

<sup>4</sup>The procedure using *Gasgano* is conceptually identical.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	23 of 132

One standard star field exposure:

```
EFOSC.2007-08-30T23:19:47.455.fits STANDARD_IMG
```

Five bias exposures:

```
EFOSC.2007-08-30T10:03:01.111.fits BIAS
EFOSC.2007-08-30T10:03:29.714.fits BIAS
EFOSC.2007-08-30T10:03:56.637.fits BIAS
EFOSC.2007-08-30T10:04:24.850.fits BIAS
EFOSC.2007-08-30T10:04:51.253.fits BIAS
```

All the listed data are meant to be obtained from the same EFOSC chip, with the same filter in use, same binning, readout mode, etc.. In this example it is assumed that filter V#641 is in use on chip "ccd40" (this is important for the association of the appropriate static calibration tables to the raw input data to be processed).

In the following, it is also assumed for simplicity that, in the *Esorex* configuration file, the flag *suppress-prefix* is set to `TRUE`, so that the product file names will just be identical to their product categories, with an extension `.fits`. Moreover, it is assumed that all the handled files (inputs and products) are located in the current directory. The only exception is represented by the standard calibration tables (e.g., star catalogs), which here are assumed to be located in `/cal/efosc`.<sup>5</sup>

In order to produce a master bias calibration, the recipe *efosc\_bias* should be used (see Section 9.1, page 52). The input SOF may be defined as follows:

File: *bias.sof*

```
EFOSC.2007-08-30T10:03:01.111.fits BIAS
EFOSC.2007-08-30T10:03:29.714.fits BIAS
EFOSC.2007-08-30T10:03:56.637.fits BIAS
EFOSC.2007-08-30T10:04:24.850.fits BIAS
EFOSC.2007-08-30T10:04:51.253.fits BIAS
```

This is the list of the raw bias frames meant to be used for the production of the master bias calibration.

The following commandline can now be given at the shell prompt:

```
esorex efosc_bias bias.sof
```

Just one product is created on disk:

**master\_bias.fits:** master bias calibration.

Different stacking methods are available and may be specified on the command line: the default is to stack frames rejecting the highest and lowest pixel values averaging the rest.

---

<sup>5</sup>The user decides where the calibration tables should be copied at installation time.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	24 of 132

A twilight sky flat master calibration is produced using the recipe *efosc\_img\_sky\_flat* (see Section 9.3, page 56). The input SOF may be defined as follows:

File: *flat.sof*

```
EFOSC.2007-08-30T23:01:46.059.fits SKY_FLAT_IMG
EFOSC.2007-08-30T23:02:22.453.fits SKY_FLAT_IMG
EFOSC.2007-08-30T23:02:59.897.fits SKY_FLAT_IMG
EFOSC.2007-08-30T23:03:38.441.fits SKY_FLAT_IMG
master_bias.fits MASTER_BIAS
```

This is the list of the twilight sky exposures meant to be used for the production of the flat field calibration, and the bias master calibration previously created with *efosc\_bias*.

The following commandline can now be given at the shell prompt:

```
esorex efosc_img_sky_flat flat.sof
```

Just one product is created on disk:

**master\_sky\_flat\_img.fits:** twilight sky master calibration.

Different stacking methods are available and may be specified on the command line: the default is to median-stack the input frames (after normalisation of each frame to its own median value).

At this point, with a flat and a bias, it is possible to reduce a scientific exposure. This is done with the recipe *efosc\_img\_science* (see Section 9.4, page 57), defining the following input set-of-frames:

File: *sci.sof*

```
EFOSC.2007-08-30T23:41:28.745.fits SCIENCE_IMG
master_bias.fits MASTER_BIAS
master_sky_flat_img.fits MASTER_SKY_FLAT_IMG
/cal/efosc/efosc_phot.fits PHOT_TABLE
```

The so-called photometric table (PHOT\_TABLE) carries information about the atmospheric extinction and spectral corrections for any of the available standard filters the instrument is equipped with. This recipe uses only the atmospheric extinction, for correcting measured *instrumental* magnitudes of detected objects to airmass zero.

The following commandline can now be given at the shell prompt:

```
esorex efosc_img_science sci.sof
```

A number of products are created on disk, mainly for check purposes:

**science\_reduced\_img.fits:** reduced scientific frame.



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	25 of 132

**phot\_background\_img.fits:** background map.

**object\_table\_sci\_img.fits:** properties of detected objects.

**sources\_sci\_img.fits:** complete source detection output (SExtractor [21]).

If a standard star field exposure is available it is possible to transform the measured instrumental magnitudes into physical magnitudes. The recipe *efosc\_zeropoint* (see Section 9.5, page 60), with the following input set-of-frames, would produce a zeropoint for the standard star frame (hopefully valid for the scientific frame too):

File: *std.sof*

```
EFOSC.2007-08-30T23:19:47.455.fits  STANDARD_IMG
master_bias.fits                    MASTER_BIAS
master_sky_flat_img.fits            MASTER_SKY_FLAT_IMG
/cal/efosc/efosc_phot.fits           PHOT_TABLE
/cal/efosc/landolt_std_UBVRI.tfits  FLX_STD_IMG
/cal/efosc/stetson_std_BVRI.fits    FLX_STD_IMG
```

The same master and static calibration files used for the scientific data reduction are used here. In addition to that, at least one photometric standard stars catalog (FLX\_STD\_IMG) must be specified.

Currently the Landolt and the Stetson catalogs are supported: if both are specified in input, as in this example, the information will be merged into a single table, eliminating common entries by choosing the ones with the smallest magnitude error. It should be noted that using simultaneously two different catalogs carries a significant risk to produce inconsistent results, as the magnitudes are not derived with the same method in both catalogs, and as a consequence common stars can differ by up to 0.2 magnitudes. The use of two catalogs is therefore strongly discouraged.

The following command line will execute the recipe:

```
esorex efosc_zeropoint std.sof
```

A number of products are created on disk, mainly for check purposes:

**standard\_reduced\_img.fits:** reduced standard field exposure.

**phot\_background\_img.fits:** background map.

**aligned\_phot.fits:** properties of detected standard stars.

**sources\_std\_img.fits:** complete source detection output (SExtractor [21]).

**debug.fits:** image with marked detected sources vs expected standard stars.

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	26 of 132

### 4.3 Example of MOS data reduction using Esorex

In this Section the reduction of spectra from a mask with several slits is described. For the case of single long-slit observations, see the next Section.

In the following, a typical EFOSC MOS data reduction procedure is described.<sup>6</sup> Note that this is an ideal session, where nothing goes wrong: for checking the quality of the results and troubleshooting, please refer to Appendix A.

It is assumed that the following data are available:

One scientific exposure:

```
EFOSC.2004-09-27T02:39:11.479.fits  SCIENCE_MOS
```

Three flat field exposures obtained with the mask used for the scientific exposure:

```
EFOSC.2004-09-27T18:59:03.641.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:00:07.828.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:01:14.252.fits  SCREEN_FLAT_MOS
```

One arc lamp exposure obtained with the mask used for the scientific exposure:

```
EFOSC.2004-09-27T19:13:03.631.fits  LAMP_MOS
```

Five bias exposures:

```
EFOSC.2004-09-27T08:00:27.821.fits  BIAS
EFOSC.2004-09-27T08:01:05.604.fits  BIAS
EFOSC.2004-09-27T08:01:44.091.fits  BIAS
EFOSC.2004-09-27T08:02:22.070.fits  BIAS
EFOSC.2004-09-27T08:03:01.042.fits  BIAS
```

All the listed data are meant to be obtained from the same EFOSC chip, with the same grism and filter in use. In this example it is assumed that grism 14 is in use (this is important for the association of the appropriate static calibration tables to the raw input data to be processed).

In the following, it is also assumed for simplicity that, in the *Esorex* configuration file, the flag *suppress-prefix* is set to `TRUE`, so that the product file names will just be identical to their product categories, with an extension `.fits`. Moreover, it is assumed that all the handled files (inputs and products) are located in the current directory. The only exception is represented by the standard calibration tables (e.g., line catalogs), which here are assumed to be located in `/cal/efosc`.<sup>7</sup>

In order to process the calibration exposures available for the scientific observation, the recipe *efosc\_calib* is used (see Section 9.7, page 70). The input SOF may be defined as follows:

<sup>6</sup>The procedure using *Gasgano* is conceptually identical.

<sup>7</sup>The user decides where the calibration tables should be copied at installation time.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	27 of 132

File: *cal.sof*

```

EFOSC.2004-09-27T08:00:27.821.fits  BIAS
EFOSC.2004-09-27T08:01:05.604.fits  BIAS
EFOSC.2004-09-27T08:01:44.091.fits  BIAS
EFOSC.2004-09-27T08:02:22.070.fits  BIAS
EFOSC.2004-09-27T08:03:01.042.fits  BIAS
EFOSC.2004-09-27T18:59:03.641.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:00:07.828.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:01:14.252.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:13:03.631.fits  LAMP_MOS
/cal/efosc/EFOSC_ACAT_14.fits       LINE_CATALOG
/cal/efosc/EFOSC_GRS_14.fits        GRISM_TABLE

```

The input BIAS frames are used to generate a median bias frame which is internally subtracted from all the input raw images, and eventually written to disk for further use. A master bias frame may also be produced using the recipe *efosc\_bias* (described in the imaging data reduction Section 4.2), or by other means (taking care of trimming the overscan regions from the final result). This own-produced master bias frame may be specified in input instead of the sequence of raw BIAS frames, using the tag MASTER\_BIAS:

File: *cal.sof*

```

master_bias.fits                    MASTER_BIAS
EFOSC.2004-09-27T18:59:03.641.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:00:07.828.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:01:14.252.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:13:03.631.fits  LAMP_MOS
/cal/efosc/EFOSC_ACAT_14.fits       LINE_CATALOG
/cal/efosc/EFOSC_GRS_14.fits        GRISM_TABLE

```

The LINE\_CATALOG and the GRISM\_TABLE are static calibration tables which are available in the calibration directories delivered with the pipeline recipes. The file EFOSC\_ACAT\_14.fits is the default catalog of reference arc lamp lines for grism 14 of the EFOSC2 instrument. This catalog may be replaced with alternative ones provided by the user, if found appropriate.

The EFOSC\_GRS\_14.fits table contains the default *efosc\_calib* recipe configuration parameters for grism 14 of the EFOSC2 instrument. If this file is not specified, appropriate values for the parameters must be set in the commandline or in the *Esorex* configuration file.

The following commandline can now be given at the shell prompt:

```
esorex efosc_calib cal.sof
```

Several products are created on disk, mainly for check purposes. The products which are necessary for the scientific data reduction are the following:

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	28 of 132

**master\_bias.fits:** master bias frame, produced only in case a sequence of raw BIAS exposures was specified in input.

**master\_norm\_flat\_mos.fits:** normalised flat field image.

**slit\_location\_mos.fits:** slit positions on the CCD.

**curv\_coeff\_mos.fits:** coefficients of the spatial curvature fitting polynomials.

**disp\_coeff\_mos.fits:** coefficients of the wavelength calibration fitting polynomials.

Products for checking the quality of the result are:

**master\_screen\_flat\_mos.fits:** sum of all the input flat field exposures.

**curv\_traces\_mos.fits:** table containing the  $x$  CCD positions of the detected spectral edges at different  $y$  CCD positions, compared with their modeling.

**delta\_image\_mos.fits:** deviation from the linear term of the wavelength calibration fitting polynomials.

**disp\_residuals\_mos.fits:** residuals for each wavelength calibration fit, produced only if the recipe configuration `--check` is set.

**disp\_residuals\_table\_mos.fits:** table containing different kinds of residuals for a sample of wavelength calibration fits.

**global\_distortion\_table.fits:** table containing the modeling of the coefficients listed in the `curv_coeff_mos.fits` and `disp_coeff_mos.fits` tables, only produced if more than 6 slits are available.

**reduced\_lamp\_mos.fits:** rectified and wavelength calibrated arc lamp image.

**spectra\_detection\_mos.fits:** result of preliminary wavelength calibration applied to the input arc lamp exposure, produced only if the recipe configuration `--check` is set.

**wavelength\_map\_mos.fits:** map of wavelengths on the CCD.

**spatial\_map\_mos.fits:** map of spatial positions on the CCD.

**slit\_map\_mos.fits:** map of the grism central wavelength, produced only if the recipe configuration `--check` is set.

**spectral\_resolution\_mos.fits:** mean spectral resolution for each reference arc lamp line.

**mapped\_screen\_flat\_mos.fits:** flat field with distortion removed.

**mapped\_norm\_flat\_mos.fits:** normalised flat field with distortion removed.

Now the scientific frame can be processed, and for this the recipe `efosc_science` is used (see Section 9.8, page 86). The following set-of-frames file may be created:

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	29 of 132

File: *sci.sof*

EFOSC.2004-09-27T02:39:11.479.fits	SCIENCE_MOS
master_bias.fits	MASTER_BIAS
master_norm_flat_mos.fits	MASTER_NORM_FLAT_MOS
disp_coeff_mos.fits	DISP_COEFF_MOS
curv_coeff_mos.fits	CURV_COEFF_MOS
slit_location_mos.fits	SLIT_LOCATION_MOS
/cal/efosc/EFOSC_GRS_14.fits	GRISM_TABLE

Note that the same (optional) GRISM\_TABLE specified in the `cal.sof` file is used here. This is advisable, even if not really mandatory

With the following command:

```
esorex efosc_science sci.sof
```

the following products are created on disk:

- mapped\_all\_sci\_mos.fits:** image with rectified and wavelength calibrated slit spectra.
- mapped\_sci\_mos.fits:** image with rectified, wavelength calibrated, and sky subtracted slit spectra.
- mapped\_sky\_sci\_mos.fits:** image with rectified and wavelength calibrated slit sky spectra.
- unmapped\_sci\_mos.fits:** image with the sky subtracted scientific spectra on the CCD.
- unmapped\_sky\_sci\_mos.fits:** image with the modeled sky spectra on the CCD.
- object\_table\_sci\_mos.fits:** slit positions on the CCD, on the mapped images, and positions of the detected objects within the slits.
- reduced\_sci\_mos.fits:** image with extracted objects spectra.
- reduced\_sky\_sci\_mos.fits:** image with sky corresponding to the extracted objects spectra.
- reduced\_error\_sci\_mos.fits:** image with the statistical errors corresponding to the extracted objects spectra.
- sky\_shifts\_slit\_sci\_mos.fits:** table containing the observed sky lines offsets that were used for adjusting the input wavelength solutions, only created if the sky line alignment was requested.
- wavelength\_map\_sci\_mos.fits:** map of wavelengths on the CCD, only created if the sky line alignment was requested.
- disp\_coeff\_sci\_mos.fits:** wavelength calibration polynomials coefficients after alignment of the solutions to the position of the sky lines, only created if the sky line alignment was requested.

Support for a spectro-photometric calibration is also available, but in this case an atmospheric extinction table (see Section 7.6, page 45) and a spectral response curve for the present instrument configuration (see SPECPHOT\_TABLE entry, page 92) must also be specified in input. Spectral response curves can be produced by applying the *efosc\_science* recipe to standard star exposures. Standard star spectra are reduced applying the long-slit data reduction strategy<sup>8</sup> which is described in the next Section.

<sup>8</sup>Standard star observations are typically performed with the long-slit configuration.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	30 of 132

#### 4.4 Example of long-slit data reduction using Esorex

Long-slit observations are used both for scientific and calibration (standard star) purposes.

The algorithms applied for data processing are slightly different from those applied in the case of a generic MOS observation: for instance, more robust methods can be used for the alignment of the dispersion solution to the sky line positions, thanks to the availability of a larger and more homogeneous statistical sample. Moreover, since the slit is long, its ends are far apart and typically not visible in the detector, and therefore they cannot be used to determine a reliable spatial curvature solution: for this reason the spatial curvature related products are not created.<sup>9</sup>

In the following example a EFOSC2 long-slit observation of a standard star is processed.<sup>10</sup> Note that this is an ideal session, where nothing goes wrong: for checking the quality of the results and troubleshooting, please refer to Appendix A.

It is assumed that the following data are available:

One standard star exposure:

```
EFOSC.2004-09-27T03:12:12.006.fits STANDARD_MOS
```

Three flat field exposures obtained with the mask used for the standard star exposure:

```
EFOSC.2004-09-27T19:22:22.308.fits SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:23:14.722.fits SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:24:52.651.fits SCREEN_FLAT_MOS
```

One arc lamp exposure obtained with the mask used for the standard star exposure:

```
EFOSC.2004-09-27T19:33:44.097.fits LAMP_MOS
```

Five bias exposures:

```
EFOSC.2004-09-27T08:00:27.821.fits BIAS
EFOSC.2004-09-27T08:01:05.604.fits BIAS
EFOSC.2004-09-27T08:01:44.091.fits BIAS
EFOSC.2004-09-27T08:02:22.070.fits BIAS
EFOSC.2004-09-27T08:03:01.042.fits BIAS
```

All the listed data are meant to be obtained with the same grism, 14, in use.

In the following, it is also assumed for simplicity that, in the *Esorex* configuration file, the flag *suppress-prefix* is set to `TRUE`, so that the product file names will just be identical to their product categories, with an extension `.fits`. Moreover, it is assumed that all the handled files (inputs and products) are located in

<sup>9</sup>In a future release it will be possible to import a curvature solution obtained from appropriate calibration masks

<sup>10</sup>In case of a scientific observation the DO categories would be the same, just replacing STANDARD with SCIENCE, and STD with SCI.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	31 of 132

the current directory. The only exception is represented by the standard calibration tables (e.g., line catalogs), which here are assumed to be located in `/cal/efosc`.<sup>11</sup>

In order to process the calibration exposures available for the standard star observation, the recipe *efosc\_calib* is used (see Section 9.7, page 70). The input SOF may be defined as follows:

File: *cal.sof*

```
EFOSC.2004-09-27T08:00:27.821.fits  BIAS
EFOSC.2004-09-27T08:01:05.604.fits  BIAS
EFOSC.2004-09-27T08:01:44.091.fits  BIAS
EFOSC.2004-09-27T08:02:22.070.fits  BIAS
EFOSC.2004-09-27T08:03:01.042.fits  BIAS
EFOSC.2004-09-27T19:22:22.308.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:23:14.722.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:24:52.651.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:33:44.097.fits  LAMP_MOS
/cal/efosc/EFOSC_ACAT_14.fits        LINE_CATALOG
/cal/efosc/EFOSC_GRS_14.fits         GRISM_TABLE
```

The input BIAS frames are used to generate a median bias frame which is internally subtracted from all the input raw images, and eventually written to disk for further use. A master bias frame may also be produced using the recipe *efosc\_bias* (described in the imaging data reduction Section 4.2), or by other means (taking care of trimming the overscan regions from the final result). This own-produced master bias frame may be specified in input instead of the sequence of raw BIAS frames, using the tag MASTER\_BIAS:

File: *cal.sof*

```
master_bias.fits                    MASTER_BIAS
EFOSC.2004-09-27T19:22:22.308.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:23:14.722.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:24:52.651.fits  SCREEN_FLAT_MOS
EFOSC.2004-09-27T19:33:44.097.fits  LAMP_MOS
/cal/efosc/EFOSC_ACAT_14.fits        LINE_CATALOG
/cal/efosc/EFOSC_GRS_14.fits         GRISM_TABLE
```

The LINE\_CATALOG and the GRISM\_TABLE are static calibration tables which are available in the calibration directories delivered with the pipeline recipes. The file `EFOSC_ACAT_14.fits` is the default catalog of reference arc lamp lines for grism 14 of the EFOSC2 instrument. This catalog may be replaced with alternative ones provided by the user, if found appropriate.

The `EFOSC_GRS_14.fits` table contains the default *efosc\_calib* recipe configuration parameters for grism 14 of the EFOSC2 instrument. If this file is not specified, appropriate values for the parameters must be set in the commandline or in the *Esorex* configuration file.

The following commandline can now be given at the shell prompt:

<sup>11</sup>The user decides where the calibration tables should be copied at installation time.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	32 of 132

```
esorex efosc_calib cal.sof
```

Several products are created on disk, mainly for check purposes. The products which are necessary for the scientific data reduction are the following:

**master\_bias.fits:** master bias frame, produced only in case a sequence of raw BIAS exposures was specified in input.

**master\_norm\_flat\_mos.fits:** normalised flat field image.

**disp\_coeff\_mos.fits:** coefficients of the wavelength calibration fitting polynomials.

Products for checking the quality of the result are:

**master\_screen\_flat\_mos.fits:** sum of all the input flat field exposures.

**delta\_image\_mos.fits:** deviation from the linear term of the wavelength calibration fitting polynomials.

**disp\_residuals\_mos.fits:** residuals for each wavelength calibration fit.

**disp\_residuals\_table\_mos.fits:** table containing different kinds of residuals for a sample of wavelength calibration fits.

**reduced\_lamp\_mos.fits:** wavelength calibrated arc lamp image.

**wavelength\_map\_mos.fits:** map of wavelengths on the CCD.

**spectra\_resolution\_mos.fits:** mean spectral resolution for each reference arc lamp line.

Now the scientific frame can be processed, and for this the recipe *efosc\_science* is used (see Section 9.8, page 86). The following set-of-frames file may be created:

File: *sci.sof*

```
EFOSC.2004-09-27T03:12:12.006.fits  STANDARD_MOS
master_bias.fits                     MASTER_BIAS
master_norm_flat_mos.fits            MASTER_NORM_FLAT_MOS
disp_coeff_mos.fits                  DISP_COEFF_MOS
/cal/efosc/EFOSC_GRS_14.fits          GRISM_TABLE
/cal/efosc/extinct_table.fits         EXTINCT_TABLE
/cal/efosc/ltt7379.fits               STD_FLUX_TABLE
```

Note that the same (optional) GRISM\_TABLE specified in the *cal.sof* file is used here. This is advisable, even if not really mandatory. An atmospheric extinction table and a standard star flux table (see Sections 7.6, page 45, and 7.7, page 45) are specified here, leading to the production of spectral efficiency and response curves for the present instrument configuration (see SPECPHOT\_TABLE entry, page 92). The response curve can be used by recipe *efosc\_science* to produce also flux calibrated extracted spectra.

With the following command (where setting *--photometry=true* implies that the produced response curve is also applied to the extracted spectra, to flux calibrate them):



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	33 of 132

```
esorex efosc_science --photometry=true sci.sof
```

the following products are created on disk:

**specphot\_table.fits:** table with efficiency and response curves.

**mapped\_all\_std\_mos.fits:** image with wavelength calibrated slit spectra.

**mapped\_std\_mos.fits:** image with wavelength calibrated and sky subtracted slit spectra.

**mapped\_flux\_std\_mos.fits:** image with flux calibrated, wavelength calibrated, and sky subtracted slit spectra.

**object\_table\_std\_mos.fits:** slit positions on the CCD, on the mapped images, and positions of the detected objects within the slits.

**reduced\_std\_mos.fits:** image with extracted objects spectra.

**reduced\_flux\_std\_mos.fits:** image with flux calibrated extracted objects spectra.

**reduced\_sky\_std\_mos.fits:** image with sky corresponding to the extracted objects spectra.

**reduced\_error\_std\_mos.fits:** image with the statistical errors corresponding to the extracted objects spectra.

**reduced\_flux\_error\_std\_mos.fits:** image with the statistical errors corresponding to the flux calibrated extracted objects spectra.

**sky\_shifts\_long\_std\_mos.fits:** table containing the observed sky lines offsets that were used for adjusting the input wavelength solutions, only created if the sky line alignment was requested.

**wavelength\_map\_std\_mos.fits:** map of wavelengths on the CCD, only created if the sky line alignment was requested.

**disp\_coeff\_std\_mos.fits:** wavelength calibration polynomials coefficients after alignment of the solutions to the position of the sky lines, only created if the sky line alignment was requested.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	34 of <a href="#">132</a>

## 5 Known Problems

Development work is still ongoing, as these recipes do not yet support important tasks such as the combination of a sequence of scientific exposures.

The automatic spectral sky subtraction is not guaranteed to always work well, especially in the case of long-slit data, or with too short MOS slits (dominated by the emission of the target): the presence of extended objects on slit would make it difficult to determine the sky signal to subtract.

Occasionally spectra may be lost to the pattern-matching algorithm: such cases will require some iteration, running the data reduction recipes with different parameter settings or editing the reference arc lamp lines catalog (adding more lines, if available). See [Appendix A](#) for more details.

The alignment of the wavelength calibration solution to the sky-lines does not give good results at very low spectral resolution ( $R < 300$ ).

The spatial curvature is not modeled for long-slit data, because it is not directly observable. This will be partially solved in one of the next pipeline releases by applying predefined (but alas, fixed) spatial curvature models. A complete solution to this problem will probably never be available.

Polarimetry modes are unsupported.

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	35 of 132

## 6 Instrument Data Description

This Section mainly deals with the appropriate classification of data used by the pipeline. This is done automatically by *Gasgano* [14], but not by *Esorex* [12]. If the pipeline user has already classified their FITS files (in biases, flat fields, science frames, etc.), there is no need to use the formal classification rules described in this Section.

The data handled by the EFOSC pipeline can be separated into *raw* frames and *calib* frames. *Raw* frames are the unprocessed output of the EFOSC2 instrument observations, while *calib* frames are anything else: either the result of the EFOSC pipeline processing (as reduced frames, master calibration frames, etc.), or obtained in other ways (as standard stars catalogs, lists of grism characteristics, etc.).

Any *raw* or *calib* frame can be classified on the basis of a set of keywords read from its header. Data classification is typically carried out by the DO or by *Gasgano*, which apply the same set of classification rules. The association of a raw frame with calibration data (*e.g.*, of a science frame with a master bias frame) can be obtained by matching the values of appropriate sets of header keywords.

Each kind of *raw* frame is typically associated to a single EFOSC pipeline recipe, *i.e.*, the recipe assigned to the reduction of that specific frame type. In the pipeline environment this recipe would be launched automatically. In some cases two recipes are assigned, one meant for the reduction of a single frame of that type, and the other for the reduction of a *stack* of frames of the same type, as happens in the case of jittered science observations.

A *calib* frame may be input to more than one EFOSC pipeline recipe, but it may be created by just one pipeline recipe (with the same exceptions mentioned above). In the automatic pipeline environment a *calib* data frame alone would not trigger the launch of any recipe.

In the following all raw EFOSC data frames are listed, together with the keywords used for their classification and correct association. The indicated *DO category* is a label assigned by the online pipeline system to any data type after it has been classified, which is then used to identify the frames listed in the *Set of Frames* (see Section 4.1.2, page 20).

The *calib* frames produced by the pipeline are listed in the description of the individual recipes producing them. The *calib* frames which are used by the pipelines, indicated also as static calibration data, are described in section 7, page 40.

Raw frames can be distinguished in *general* frames, *IMG* frames, and *MOS* frames. Their intended use is implicitly defined by the assigned recipe.

### 6.1 General frames

These are data that are in principle independent of the instrument mode (direct imaging, spectroscopy), as is the case for bias exposures.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	36 of 132

- **Bias:**

DO category: BIAS

Processed by: efosc\_bias, efosc\_calib

Classification keywords:

DPR CATG = CALIB

DPR TYPE = BIAS

Association keywords:

DET READ CLOCK

DET WIN1 BINX

DET WIN1 BINY

DET OUTPUTS

DET WIN1 STRX

DET WIN1 STRY

DET WIN1 NX

DET WIN1 NY

DET CHIP1 ID

Note:

Readout mode

x-binning

y-binning

No of outputs

Window start in x

Window start in y

No of pixels in x

No of pixels in y

Chip identifier

## 6.2 IMG frames

The IMG mode performs direct imaging applying different filters.

- **Screen flat field:**

DO category: SCREEN\_FLAT\_IMG

Processed by: efosc\_img\_screen\_flat

Classification keywords:

DPR CATG = CALIB

DPR TYPE = DOME

DPR TECH = IMAGE

Association keywords:

*None: unused in processing*

Note:

- **Sky flat field:**

DO category: SKY\_FLAT\_IMG

Processed by: efosc\_img\_sky\_flat

Classification keywords:

DPR CATG = CALIB DPR

TYPE = SKY,FLAT

DPR TECH = IMAGE

Association keywords:

DET CHIP1 ID

DET READ CLOCK

DET WIN1 BINX

DET WIN1 BINY

DET OUTPUTS

DET WIN1 STRX

DET WIN1 STRY

DET WIN1 NX

DET WIN1 NY

Note:

Chip identifier

Readout mode

x-binning

y-binning

No of outputs

Window start in x

Window start in y

No of pixels in x

No of pixels in y

- **Scientific observation:**

DO category: SCIENCE\_IMG

Processed by: efosc\_img\_science

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	37 of 132

**Classification keywords:**

DPR CATG = SCIENCE  
DPR TYPE = OBJECT  
DPR TECH = IMAGE

**Association keywords:**

INS FILT1 NAME  
DET READ CLOCK  
INS COLL NAME  
DET WIN1 BINX  
DET WIN1 BINY  
DET OUTPUTS  
DET WIN1 STRX  
DET WIN1 STRY  
DET WIN1 NX  
DET WIN1 NY  
DET CHIP1 ID

**Note:**

Filter used  
Readout mode  
Collimator name  
x-binning  
y-binning  
No of outputs  
Window start in x  
Window start in y  
No of pixels in x  
No of pixels in y  
Chip identifier

- **Standard star field:**

DO category: STANDARD\_IMG  
Processed by: efosc\_zeropoint

**Classification keywords:**

DPR CATG = SCIENCE  
DPR TYPE = STD  
DPR TECH = IMAGE

**Association keywords:**

INS FILT1 NAME  
DET READ CLOCK  
INS COLL NAME  
DET WIN1 BINX  
DET WIN1 BINY  
DET OUTPUTS  
DET WIN1 STRX  
DET WIN1 STRY  
DET WIN1 NX  
DET WIN1 NY  
DET CHIP1 ID

**Note:**

Filter used  
Readout mode  
Collimator name  
x-binning  
y-binning  
No of outputs  
Window start in x  
Window start in y  
No of pixels in x  
No of pixels in y  
Chip identifier

## 6.3 MOS frames

The MOS mode performs multi-object spectroscopy using a mask of slits.

- **Screen flat field:**

DO category: SCREEN\_FLAT\_MOS  
Processed by: efosc\_calib

**Classification keywords:**

DPR CATG = CALIB  
DPR TYPE = FLAT  
DPR TECH = SPECTRUM

**Association keywords:**

DET CHIP1 ID  
INS GRIS1 NAME  
DET READ CLOCK  
DET WIN1 BINX  
DET WIN1 BINY  
DET OUTPUTS  
DET WIN1 STRX  
DET WIN1 STRY

**Note:**

Chip identifier  
Grism used  
Readout mode  
x-binning  
y-binning  
No of outputs  
Window start in x  
Window start in y

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	<b>Doc:</b>	VLT-MAN-ESO-19520-5222
		<b>Issue:</b>	Issue 1.1
		<b>Date:</b>	Date 2011-02-02
		<b>Page:</b>	38 of 132

DET WIN1 NX                      No of pixels in x  
DET WIN1 NY                      No of pixels in y

- **Arc lamp spectrum:**

DO category: LAMP\_MOS  
Processed by: efosc\_calib

<b>Classification keywords:</b>	<b>Association keywords:</b>	<b>Note:</b>
DPR CATG = CALIB	DET CHIP1 ID	Chip identifier
DPR TYPE = WAVE	INS GRIS1 NAME	Grism used
DPR TECH = SPECTRUM	DET READ CLOCK	Readout mode
	DET WIN1 BINX	x-binning
	DET WIN1 BINY	y-binning
	DET OUTPUTS	No of outputs
	DET WIN1 STRX	Window start in x
	DET WIN1 STRY	Window start in y
	DET WIN1 NX	No of pixels in x
	DET WIN1 NY	No of pixels in y

- **Scientific observation:**

DO category: SCIENCE\_MOS  
Processed by: efosc\_science, efosc\_extract

<b>Classification keywords:</b>	<b>Association keywords:</b>	<b>Note:</b>
DPR CATG = SCIENCE	DET CHIP1 ID	Chip identifier
DPR TYPE = OBJECT	INS GRIS1 NAME	Grism used
DPR TECH = SPECTRUM	INS FILT1 NAME	Filter used
	DET READ CLOCK	Readout mode
	DET WIN1 BINX	x-binning
	DET WIN1 BINY	y-binning
	DET OUTPUTS	No of outputs
	DET WIN1 STRX	Window start in x
	DET WIN1 STRY	Window start in y
	DET WIN1 NX	No of pixels in x
	DET WIN1 NY	No of pixels in y

- **Standard star spectrum:**

DO category: STANDARD\_MOS  
Processed by: efosc\_science, efosc\_extract

<b>Classification keywords:</b>	<b>Association keywords:</b>	<b>Note:</b>
DPR CATG = SCIENCE	DET CHIP1 ID	Chip identifier
DPR TYPE = STD	INS GRIS1 NAME	Grism used
DPR TECH = SPECTRUM	INS FILT1 NAME	Filter used
	DET READ CLOCK	Readout mode
	DET WIN1 BINX	x-binning
	DET WIN1 BINY	y-binning
	DET OUTPUTS	No of outputs

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	39 of <a href="#">132</a>

DET WIN1 STRX	Window start in x
DET WIN1 STRY	Window start in y
DET WIN1 NX	No of pixels in x
DET WIN1 NY	No of pixels in y

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	40 of 132

## 7 Static Calibration Data

In the following all the EFOSC static calibration tables related to direct imaging and spectroscopic modes are listed. The indicated *DO category*, written to the FITS header keyword PRO.CATG, is a label assigned to any data type after it has been classified. This label is then used to identify the frames listed in the *set-of-frames* (see Section 4.1.2, page 20).

### 7.1 Photometric table

DO category: PHOT\_TABLE

This table lists parameters related to each standard filter in use in the EFOSC2 instrument. This table would in principle depends on the CCD in use. Currently available is the table `efosc_phot.fits` valid for DET CHIP1 ID = 'ccd40'. This table contains the following columns:

<b>filter:</b>	Name of filter
<b>ext:</b>	Atmospheric extinction coefficient (mag/airmass)
<b>dext:</b>	Error on atmospheric extinction coefficient (mag/airmass)
<b>col:</b>	Color correction term
<b>dcol:</b>	Error on color term
<b>zpoint:</b>	Photometric night zeropoint
<b>dzpoint:</b>	Error on photometric night zeropoint

To clarify the terminology used here: more than one filter may correspond to each of the standard bands, (U,B,V,R,I). In the EFOSC2 instrument the following filters are or have been available:

<i>Filter</i>	<i>Band</i>
U#640	U
B#639	B
g#782	V
V#641	V
r#786	R
R#642	R
i#705	I
z#623	I
r#784	R

For each filter, beyond the corresponding atmospheric extinction and expected zeropoint, a color term is given in the column **col** of the photometric table. The color term is a correction factor which is applied to the color index of a given star, in order to compensate for the differences between the EFOSC2 filters and the standard UBVRI bands using the linear approximation:

$$M_{s,b}^* = M_{s,b} - \Gamma_f \cdot C_{s,b}$$



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	41 of 132

where  $M_{s,b}$  is the catalog magnitude in the band  $b$  of a star  $s$ ,  $M_{s,b}^*$  the color corrected magnitude,  $\Gamma_f$  the linear color correction term for the filter  $f$ , and  $C_{s,b}$  the color index associated to the band  $b$  for the star  $s$ . A color index is conventionally associated to each band  $b$  as in the following table:

U	U-B
B	B-V
V	B-V
R	V-R
I	V-R

## 7.2 Photometric standard stars catalog

DO category: FLX\_STD\_IMG

This table is a list of photometric standard stars parameters. Currently two catalogs are included in the static calibrations coming with the pipeline: selected UBVRI photometric standard stars from Landolt [24], and all entries from the Stetson's photometric standard stars catalog [26] [27], respectively in the files `landolt_std_UBVRI.fits` and `stetson_std_BVRI.fits`

The Landolt table lists U,B,V,R,I magnitudes and B-V, U-B, V-R, R-I, V-I for each star. Only the errors of the color indexes and the V band magnitude are provided. The pipeline assumes the V band error for all magnitudes, and will use the color index error when using directly a color index. In any case, the catalog magnitude error is generally not a dominant contribution to the total error on the zeropoint computed by the pipeline.

The Stetson table lists only B,V,R,I magnitudes (no U magnitudes), and independent errors are provided for each measurement. Color indexes are not provided directly.

The pipeline recipes use whatever catalog is specified in input, either Landolt's or Stetson's, or even both. If both catalogs are specified, they are merged before being used. In the merged catalog, if two stars are within 5 arcseconds they are considered identical and the one with the largest magnitude error is removed.<sup>12</sup>

When a catalog is loaded, a  $G$  magnitude is added to the (merged) catalog applying the relation

$$G = V + 0.56(B - V) - 0.12$$

as in Fukugita (1996) [25]<sup>13</sup>. In addition to that, a linear color correction is applied to the listed magnitudes to adapt them to the filter used in the standard star field observation (see previous Section). The error propagation is performed according to which uncorrelated errors are available. In order to do this, the generic form of the correction

$$M^* = M - \Gamma \cdot C$$

<sup>12</sup>It should be noted that using simultaneously two different catalogs carries a significant risk to produce inconsistent results, as the magnitudes are not derived with the same method in both catalogs, and as a consequence common stars can differ by up to 0.2 magnitudes. The use of two catalogs is therefore strongly discouraged.

<sup>13</sup>Admittedly, this is an unnecessary complication: treating the Gunn  $g$  filter in the context of the standard V band would have had the pipeline to compute a  $\Gamma$  around 0.56 and a zeropoint off by about 0.12 mag – reintroducing implicitly Fukugita's relation. For the moment, however, in the following treatment a reference to some "G" band defined as above will still be made. This just means that the pipeline computes the deviations from Fukugita's relation for the EFOSC2  $g\#782$  filter with respect to an ideal G band.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	42 of 132

(see previous Section) is expressed in terms of directly measured quantities. In the Landolt catalog case it will be:

$$\begin{aligned}
U^* &= V + (B - V) + (U - B) - \Gamma \cdot (U - B) \\
B^* &= V + (B - V) - \Gamma \cdot (B - V) \\
G^* &= V + (0.56 - \Gamma) \cdot (B - V) - 0.12 \quad (\text{Fukugita, 1996}) \\
V^* &= V - \Gamma \cdot (B - V) \\
R^* &= V - (V - R) - \Gamma \cdot (V - R) \\
I^* &= V - (V - I) - \Gamma \cdot (V - R)
\end{aligned}$$

which leads to the variances

$$\begin{aligned}
(\Delta U^*)^2 &= \Delta V^2 + \Delta(B - V)^2 + (1 - \Gamma)^2 \Delta(U - B)^2 + (U - B)^2 \Delta \Gamma^2 \\
(\Delta B^*)^2 &= \Delta V^2 + (1 - \Gamma)^2 \Delta(B - V)^2 + (B - V)^2 \Delta \Gamma^2 \\
(\Delta G^*)^2 &= \Delta V^2 + (0.56 - \Gamma)^2 \Delta(B - V)^2 + (B - V)^2 \Delta \Gamma^2 \\
(\Delta V^*)^2 &= \Delta V^2 + \Gamma^2 \Delta(B - V)^2 + (B - V)^2 \Delta \Gamma^2 \\
(\Delta R^*)^2 &= \Delta V^2 + (1 - \Gamma)^2 \Delta(V - R)^2 + (V - R)^2 \Delta \Gamma^2 \\
(\Delta I^*)^2 &= \Delta V^2 + \Delta(V - I)^2 + \Gamma^2 \Delta(V - R)^2 + (V - R)^2 \Delta \Gamma^2
\end{aligned}$$

Similarly, in the Stetson catalog case it will be:

$$\begin{aligned}
U^* &= (1 - \Gamma) \cdot U + \Gamma \cdot B \\
B^* &= (1 - \Gamma) \cdot B + \Gamma \cdot V \\
G^* &= V + (0.56 - \Gamma) \cdot (B - V) - 0.12 \quad (\text{Fukugita, 1996}) \\
V^* &= (1 + \Gamma) \cdot V - \Gamma \cdot B \\
R^* &= (1 + \Gamma) \cdot R - \Gamma \cdot V \\
I^* &= I + \Gamma \cdot R - \Gamma \cdot V
\end{aligned}$$

which leads to the variances

$$\begin{aligned}
(\Delta U^*)^2 &= (1 - \Gamma)^2 \Delta U^2 + (B - U)^2 \Delta \Gamma^2 + \Gamma^2 \Delta B^2 \\
(\Delta B^*)^2 &= (1 - \Gamma)^2 \Delta B^2 + (V - B)^2 \Delta \Gamma^2 + \Gamma^2 \Delta V^2 \\
(\Delta G^*)^2 &= (0.44 + \Gamma)^2 \Delta V^2 + (V - B)^2 \Delta \Gamma^2 + (0.56 - \Gamma) \Delta B^2 \\
(\Delta V^*)^2 &= (1 + \Gamma)^2 \Delta V^2 + (V - B)^2 \Delta \Gamma^2 + \Gamma^2 \Delta B^2 \\
(\Delta R^*)^2 &= (1 + \Gamma)^2 \Delta R^2 + (R - V)^2 \Delta \Gamma^2 + \Gamma^2 \Delta V^2 \\
(\Delta I^*)^2 &= \Delta I^2 + \Gamma^2 \Delta R^2 + (R - V)^2 \Delta \Gamma^2 + \Gamma^2 \Delta V^2
\end{aligned}$$

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	43 of 132

### 7.3 Grism table

DO category: GRISM\_TABLE

This table defines a subset of recipe configuration parameters controlling the way spectra are extracted for any particular grism. The table consists of a single row of values labeled with the parameters names. A standard grism table is provided for each EFOSC2 grism: this table is named following the convention:

EFOSC\_GRS\_<grism ID>\_<filter NAME>.fits

For instance, the standard grism table for EFOSC2 grism #14 and no filter is named

EFOSC\_GRS\_14.fits

If a grism table is used, it will modify the recipe parameters with its new values, with the exception of those which are explicitly given on the command line. Without a grism table, the input recipe parameters values will just be read from the command line, or from an *esorex* configuration file if present, or from their generic default values (that are rarely meaningful). The configuration parameters included in the grism table are the following:

<i>--dispersion</i>	rough expected spectral dispersion
<i>--peakdetection</i>	threshold for preliminary peak detection
<i>--wdegree</i>	polynomial degree for wavelength calibration
<i>--cdegree</i>	polynomial degree for spatial curvature
<i>--startwavelength</i>	start wavelength for spectral extraction
<i>--endwavelength</i>	end wavelength for spectral extraction
<i>--reference</i>	reference wavelength

A complete description of these parameters is given in Section 9.7.3, page 80.

### 7.4 Arc lamp lines catalog

DO category: LINE\_CATALOG

This table contains a set of reference wavelengths (in Ångstrom) for the arc lamp used. The only requirement for this table is to contain a column listing such wavelengths, whose name may be specified using the *efosc\_recipe* configuration parameter *--wcolumn* (see Section 9.7.3, page 80). A standard line catalog is also provided for each EFOSC2 grism: this table is named following the convention:

EFOSC\_ACAT\_<grism ID>.fits

For instance, the arc lamp line catalog for EFOSC2 grism #3 is named

EFOSC\_ACAT\_3.fits

In practice, however, the correct (standard) line catalog can be associated to a given arc lamp frame using the FITS keyword ESO INS GRIS1 NAME, found both in the line catalog and in the raw input frames headers.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	44 of 132

## 7.5 Global distortion table

DO category: GLOBAL\_DISTORTION\_TABLE

Table containing the modeling of the coefficients of the local distortion models listed in the DISP\_COEFF\_MOS and the CURV\_COEFF\_MOS tables (see page 71). This table is used for enabling the on-line processing of scientific data with the recipes *efosc\_extract* and *fors\_pmos\_extract*, when appropriate (day) calibrations are not yet available. It is also used by the recipe *fors\_pmos\_calib*, in order to guarantee the correct identification of the matching ordinary and extraordinary beam pairs in the calibration frames.<sup>14</sup>

Conventionally this table consists of 6 columns and 10 rows. Each row corresponds to the modeling of one coefficient of the original polynomial coefficients belonging to the local distortion solutions (presumably obtained with a calibration mask), performed by fitting a bivariate polynomial:

$$c_r = \sum_{i=0}^2 \sum_{j=0}^{2-i} a_{ij} x^i y^j$$

where  $r$  is the table row number (counted from 0) and  $c_r$  is a polynomial coefficient of a local solution. For  $r = 0$  and  $r > 6$  ( $x, y$ ) are positions on the telescope focal plane (e.g., on a mask), otherwise they are positions on the CCD. The first 6 table rows are a global description of the dispersion solution up to the fifth polynomial degree; these rows are followed by a row where just the first element is assigned the value of the central wavelength used for the given dispersion solution. The remaining 3 rows are a global description of the spatial curvature up to the second polynomial degree. The local dispersion solutions could be obtained with:

$$x = \sum_{r=0}^5 c_r (\lambda - \lambda_o)^r$$

where  $x$  is the  $x$  CCD pixel position and  $\lambda_o$  is the central wavelength of the grism used. The local spatial curvature solutions could be obtained with:

$$y = \sum_{r=7}^9 c_r x^{(r-7)}$$

where  $y$  is the  $y$  CCD pixel position and  $x$  is obtained with the previous formula.

The global distortion table columns are labeled a00, a01, a02, a10, a11, a20, indicating the coefficients of the fitting bivariate polynomials.

The global distortion table is produced by the *efosc\_calib* recipe with the tag GLOBAL\_DISTORTION\_TABLE (see Section 9.7, page 70). When a high quality global distortion table is selected and inserted in the static calibrations directory, these files are named according to the following convention:

EFOSC\_DIST\_<grism ID>.fits

For instance, the global distortion table for the EFOSC2 grism #10 is named

<sup>14</sup>Point pattern matching is generally inapplicable to slits identification in this case, because a polarimetric observation is typically carried out with all slitlets at the same offset.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	45 of 132

EFOSC\_DIST\_10.fits

In practice, the correct global distortion table can be associated to a given scientific frame using the FITS keywords `ESO INS GRIS1 NAME`, found both in the table and in the raw input frames headers.

## 7.6 Atmospheric extinction table

Currently the atmospheric extinction table valid for La Silla is made available in the calibration directory, in a file named `efosc_extinct_table.fits`.

This table includes the following columns:

<b>wave:</b>	Wavelength (Å)
<b>extinction:</b>	Atmospheric extinction (mag/airmass)

## 7.7 Standard star flux table

A set of standard star flux tables, corresponding to the 40 spectro-photometric standard stars which are included in the EFOSC2 calibration plan [5], is available in the calibration directory.

A standard star flux table includes the following columns:

<b>wave:</b>	Wavelength (Å)
<b>flux:</b>	Flux ( $10^{-16}$ erg cm <sup>-2</sup> s <sup>-1</sup> Å <sup>-1</sup> )
<b>bin:</b>	Bin width (Å)

In some tables the bin width is not available, and it is set to zero.

The names of the available standard star flux tables, and the name of the standard stars as reported in the FITS header keyword `ESO OBS TARG NAME`, are listed in Table 7.7.1.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	46 of 132

File name	Target name	Catalog
bd25d4655.tfits	BD+25d4655	Oke (1990)
bd28d4211.tfits	BD+28d4211	Oke (1990)
bd33d2642.tfits	BD+33d2642	Oke (1990)
bpm16274.fits	BPM16274	Hamuy et al. (1992, 1994)
cd32d9927.tfits	CD-32-9927	Hamuy et al. (1992, 1994)
eg21.tfits	EG-21	Hamuy et al. (1992, 1994)
eg274.tfits	EG-274	Hamuy et al. (1992, 1994)
feige110.tfits	Feige-110	Hamuy et al. (1992, 1994)
feige56.tfits	Feige-56	Hamuy et al. (1992, 1994)
feige66.tfits	Feige-66	Oke (1990)
feige67.tfits	Feige-67	Oke (1990)
g138_31.fits	G138-31	Oke (1990)
g158_100.tfits	G-158-100	Oke (1990)
g60_54.fits	G60-54	Oke (1990)
g93_48.tfits	G-93-48	Oke (unpublished)
gd108.tfits	GD-108	Oke (1990)
gd248.fits	GD248	Oke (1990)
gd50.tfits	GD-50	Oke (1990)
gd71.fits	GD71	Bohlin et al. (1995)
hd49798.fits	HD49798	Bohlin et al. (1995)
hilt600.tfits	Hiltner-600	Hamuy et al. (1992, 1994)
hz2.tfits	Hz-2	Oke (unpublished)
hz21.fits	HZ21	Bohlin et al. (1995)
hz4.fits	HZ4	Bohlin et al. (1995)
hz44.tfits	Hz-44	Oke (1990)
lb227.fits	LB227	Bohlin et al. (1995)
lds749b.tfits	LDS-749b	Oke (1990)
ltd1020.tfits	LTT-1020	Hamuy et al. (1992, 1994)
ltd1788.tfits	LTT-1788	Hamuy et al. (1992, 1994)
ltd2415.tfits	LTT-2415	Hamuy et al. (1992, 1994)
ltd3218.fits	LTT3218	Hamuy et al. (1992, 1994)
ltd377.tfits	LTT-377	Hamuy et al. (1992, 1994)
ltd3864.tfits	LTT-3864	Hamuy et al. (1992, 1994)
ltd4816.tfits	LTT-4816	Hamuy et al. (1992, 1994)
ltd6248.tfits	LTT-6248	Hamuy et al. (1992, 1994)
ltd7379.tfits	LTT-7379	Hamuy et al. (1992, 1994)
ltd7987.tfits	LTT-7987	Hamuy et al. (1992, 1994)
ltd9239.tfits	LTT-9239	Hamuy et al. (1992, 1994)
ltd9491.tfits	LTT-9491	Hamuy et al. (1992, 1994)
ngc7293.tfits	NGC-7293	Oke (1990)

Table 7.7.1: *Spectro-photometric standard stars in the EFOSC2 Calibration Plan. Full references are: Oke, 1990, AJ 99, 1621; Hamuy et al., 1992, PASP 104, 533; Hamuy et al., 1994, PASP 106, 566; Bohlin et al., 1995, AJ 110, 1316. See also <http://www.eso.org/sci/observing/tools/standards/spectra/>*

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	47 of 132

## 8 Data Reduction

Besides the usual data reduction steps, such as master bias subtraction, flat fielding, source detection and extraction, etc., two major aspects characterise the EFOSC instrument pipeline:

1. Many of the EFOSC pipeline recipes are based on pattern-matching techniques, in the attempt to make the algorithms more robust and instrument independent.
2. The pipeline recipes related to imaging data reduction support a complete propagation of photonic noise and CCD readout noise to all of its products. In the spectral data reduction part errors are propagated less rigorously, being estimated on the final products neglecting the errors introduced by both flat fielding and master bias subtraction. See Section 10.1, page 99, for more about the way errors are propagated.

A more detailed description of the applied algorithms is given in Section 10, page 99. Here just an overview of the data reduction cascade is provided.

### 8.1 Imaging data reduction overview

Six recipes are available for the reduction of EFOSC imaging data:

**efosc\_bias**, to compute a master bias frame from a set of raw bias exposures. This recipe is shared with the spectroscopic data reduction.

**efosc\_img\_sky\_flat**, to compute a master sky flat frame from a master bias frame and a set of raw twilight sky exposures.

**efosc\_img\_screen\_flat**, to compute a master screen flat frame from a master bias frame and a set of raw dome flat lamp exposures. The screen flat field is not well suited for flat field correction, and it is not applied to the data. This recipe is just used for instrument quality control.

**efosc\_img\_science**, to reduce a scientific exposure.

**efosc\_zeropoint**, to estimate a zeropoint and an atmospheric extinction from a standard star field exposure.

**efosc\_photometry**, to determine the systematic errors of a master sky flat field frame, on the basis of several (dithered) standard star field exposures corrected with that flat field frame. The corrected flat field may allow for a more accurate photometric correction. Moreover, this recipe enables the determination of physical parameters related to photometry, such as color term filter correction, atmospheric extinction, and (true) instrument zeropoint.

#### 8.1.1 Required input data

The input data to the recipe *efosc\_bias* is just a sequence of raw bias exposures. The product will be a bias master calibration frame to be used for the bias correction in the next reduction steps.





<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	49 of 132

identified sources, a background map, and a computed zeropoint will be produced.

The recipe *efosc\_photometry* can be used to process source lists produced in several runs of the recipe *efosc\_zeropoint*. This recipe is basically fitting instrumental and physical properties of the stars to extract information about the instrument response and the atmosphere. In particular this recipe may be used to determine the atmospheric extinction, the filter-dependent color correction, the instrument zeropoint, and the systematic deviation from "flatness" of a flat field.

### 8.1.2 Reduction cascade

The possible data reduction paths which can be followed using the imaging data reduction recipes are shown in image 8.1.1. The recipe *efosc\_img\_screen\_flat* is not shown, because it is not part of the (typical) data reduction flows.

## 8.2 Spectral data reduction overview

The EFOOSC spectroscopic pipeline is based on a set of 4 stand-alone recipes. Only 3 of them are involved in the off-line data reduction cascade: the *efosc\_extract* recipe is just meant for on-line data reduction. The available recipes are the following:

**efosc\_bias**, to compute a master bias frame from a set of raw bias exposures. This recipe is shared with the imaging pipeline.

**efosc\_calib**, to evaluate the spectral extraction mask on the basis of flat and arc calibration lamp exposures, and to create a normalised flat field frame.

**efosc\_science**, to apply the extraction mask and the normalised flat field to the scientific exposures.

**efosc\_extract**, identical to recipe *efosc\_science*, but used for the on-line data reduction based on fixed global optical and spectral distortion models.

### 8.2.1 Required input data

The input data to the recipe *efosc\_calib* are:

- a sequence of raw flat exposures,
- one raw arc lamp exposure,
- one master bias frame, or a sequence of raw bias exposures, and,
- one arc lamp reference lines catalog.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	50 of 132

where it is expected that flat and arc lamp exposures have been taken quasi-simultaneously, i.e., without changes in the instrument mechanical configuration (moving masks, changing flexures, etc.), to guarantee that they are affected by the same instrument distortions.

The products of recipe *efosc\_calib* depend on the nature of the input data (MOS or long slit, number of available slits, etc.):

- wavelength calibration local models,
- wavelength calibration residuals,
- spatial curvature local models,
- residuals of flat field spectra tracing,
- optical and spectral global distortion model,
- map of wavelengths for each CCD pixel,
- map of spatial coordinate along a slit for each CCD pixel,
- extracted arc lamp spectra (i.e., rebinned at constant wavelength step),
- location of slits on CCD, and on extracted arc lamp spectra image,
- master flat field,
- normalised master flat field, and,
- spectral resolution table.

The input data to the recipe *efosc\_science* depend on the nature of the data to reduce (MOS or long slit, number of available slits, etc.), and not all of them are always required (see Section 9 for more details). At best the following input might be required:

- one scientific exposure, or alternatively one spectrophotometric standard star exposure,
- one master bias frame,
- location of slits on CCD,
- spatial curvature local models, and,
- wavelength calibration local models.

All inputs but the first one are typically produced by *efosc\_calib*.

The products of recipe *efosc\_science* depend on what is requested: for instance, an upgrade of the wavelength calibration is only provided in case its alignment to a set of available sky lines is requested. In general the following products are created:

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	51 of <a href="#">132</a>

- upgraded wavelength calibration local models,
- upgraded map of wavelengths for each CCD pixel,
- upgraded slit locations on CCD and on rectified image,
- sky lines offsets against expected positions,
- sky subtracted scientific spectra on CCD,
- model sky spectra mapped on CCD,
- extracted slit spectra,
- extracted and sky subtracted slit spectra,
- location of detected objects on extracted slit spectra,
- optimally extracted scientific objects,
- sky spectra corresponding to extracted objects, and,
- error spectra of extracted objects.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	52 of 132

## 9 Pipeline Recipes Interfaces

In this Section a detailed description of the EFOOSC pipeline recipes interfaces is given, with a complete specification of the recipes usage, their input, output, and configuration parameters. For a overview of the available pipeline recipes, please see Section 8, page 47.

### 9.1 efosc\_bias

The EFOOSC pipeline recipe *efosc\_bias* is used to create a bias master calibration frame from a set of raw bias frames. The overscan regions, if present, are removed from the result.

#### 9.1.1 Input files

**BIAS:** *required* set of raw, unprocessed bias frames.

#### 9.1.2 Output files

**MASTER\_BIAS:** Bias master calibration frame.

Configuration parameters directly affecting this product are: *--stack\_method*.

#### 9.1.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_bias* recipe will process the input frames.

*--stack\_method*: Frames combination method. (**average** = simple average of all input frames, **median** = median stacking of all input frames, **minmax** = stacking frames with minmax rejection, **ksigma** = average frames with k-sigma clipping). *Default*: **minmax**

This parameter defines the way the frames will be stacked.

If *--stack\_method* is set to *minmax*, the following parameters become relevant:

*--minrejection*: Number of lowest values to be rejected. *Default*: 1

For each pixel position, the number of lowest pixel values specified here are rejected before computing the mean of the remaining pixel values.

*--maxrejection*: Number of highest values to be rejected. *Default*: 1

For each pixel position, the number of highest pixel values specified here are rejected before computing the mean of the remaining pixel values. The sum of the number of highest and lowest rejected pixels should be less than the number of input frames.

If *--stack\_method* is set to *ksigma*, the following parameters become relevant:

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	53 of 132

--*klow*: Number of sigmas for lower values rejection. *Default*: 3.0

For each pixel position, a robust determination of the standard deviation from the *median* pixel value is made. All pixel values with a negative residual greater than the specified number of sigmas are rejected, the other values are averaged.

--*khigh*: Number of sigmas for upper values rejection. *Default*: 3.0

For each pixel position, a robust determination of the standard deviation from the *median* pixel value is made. All pixel values with a positive residual greater than the specified number of sigmas are rejected, the other values are averaged.

--*kiter*: Maximum number of iterations. *Default*: 999

Maximum number of iterations of the rejection process. The iteration stops as soon as no outliers are detected, or when reaching the maximum number of iterations. At each iteration the median value and the standard deviation are recomputed, and a new k-sigma rejection is applied.

#### 9.1.4 Quality control parameters

Currently the following QC parameters are evaluated by the *efosc\_bias* recipe.

**QC BIAS LEVEL:** Bias level. *Units*: ADU

Median value of all pixels of the first raw bias in the input set-of-frames.

**QC RON:** Readout noise. *Units*: ADU

The difference between the first and the second input raw biases is computed. The standard deviation of the pixel values of this difference, divided by  $\sqrt{2}$ , is taken as the RON.

**QC BIAS FPN:** Bias fixed pattern noise. *Units*: ADU

The difference between the first two input raw bias frames, the second one shifted by  $10 \times 10$  pixels in the increasing X- and Y-directions, is computed (where possible). The variance of the difference frame includes contributions of both fixed pattern and read out noise. The standard deviation of the difference is computed and divided by  $\sqrt{2}$ . The readout noise contribution QC RON is then quadratically subtracted from the result.

**QC BIAS STRUCT:** Bias structure. *Units*: ADU

The standard deviation of the pixel values of the first input raw bias is computed. This is the combination of structure, fixed pattern, and readout noise. The readout noise QC RON and the fixed pattern QC BIAS FPN contributions are then quadratically subtracted.

**QC MBIAS LEVEL:** Master bias level. *Units*: ADU

The median value of all pixels of the product master bias.

**QC MBIAS RONEXP:** Expected master bias readout noise. *Units*: ADU

Propagation of the measured RON (QC RON) according to the number of raw bias frames, and supplied stacking method.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	54 of 132

**QC MBIAS NOISE:** Master bias noise. *Units:* ADU

The standard deviation of the pixel values from the master bias median level is determined, excluding from the computation all values that differ from it more than  $3 \times \text{QC MBIAS RONEXP}$ . This is done in the attempt to minimise deviations not caused by RON.

**QC MBIAS NRATIO:** Master bias ratio observed/expected noise. *Units:* None

Ratio between QC MBIAS NOISE and QC MBIAS RONEXP. This ratio is expected to be 1, but it may be less than 1 because of RON overestimation due to incoherent pickup noise, or more than 1 in case of coherent pickup noise that would remain unchanged on the result master bias.

**QC MBIAS STRUCT:** Structure of master bias. *Units:* ADU

Standard deviation of all master bias pixels values minus the value of QC MBIAS NOISE (geometrically subtracted).

## 9.2 efosc\_img\_screen\_flat

The EFOSC pipeline recipe *efosc\_img\_screen\_flat* is used to create a screen flat field master calibration frame from a set of raw screen flat field frames. After bias subtraction, the input frames are combined applying the specified stack method. The overscan regions, if present, are removed from the result. The combined frame is then normalised dividing it by its large scale illumination trend. The large scale trend is obtained by applying a median filter with a large kernel, or by polynomial fitting.

### 9.2.1 Input files

**SCREEN\_FLAT\_IMG:** *required* set of raw, unprocessed screen flat field frames.

**MASTER\_BIAS:** *required* master bias frame. Just one should be given.

### 9.2.2 Output files

**MASTER\_SCREEN\_FLAT\_IMG:** Screen flat field master calibration frame.

Configuration parameters directly affecting this product are: *--stack\_method*, *--xradius*, *--yradius*, *--degree*, and *--sampling*.

### 9.2.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_img\_screen\_flat* recipe will process the input frames.

*--stack\_method*: Frames combination method. *Default:* **average**

See explanation in recipe *efosc\_bias* configuration parameters (Section 9.1.3, page 52).

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	55 of 132

--*xradius*: Median filter *x* radius (unbinnedpixels). *Default*: 50 pixel

See the --*yradius* parameter

--*yradius*: Median filter *y* radius (unbinnedpixels). *Default*: 50 pixel

These parameters define the size of the runningbox used for smoothing the flat field for determining the large scale trend to remove. These parameters are ignored if the --*degree* parameter is greater than zero.

--*degree*: Degree of bivariate fitting polynomial. *Default*: -1

If this parameter is greater or equal 0 a polynomial with the specified degree will be fitted to the illuminated part of the CCD for determining the flat field large scale trend to remove.

--*sampling*: Sampling interval for fitting. *Default*: 100

If the parameter --*degree* is greater than 0, a polynomial will be fitted to the illuminated part of the CCD, sampling pixel values at the specified step.

#### 9.2.4 Quality control parameters

Currently the following QC parameters, used by PSO and DPD, are evaluated by the *efosc\_img\_screen\_flat* recipe.

**QC OVEREXPO:** Percentage of overexposed pixels. *Units*: none

A saturated pixel is defined as a pixel having value either 65535 or 0 ADUs in a raw frame. In its practical implementation, a saturated pixel is identified by having a value either greater than 65534 or less than 1 ADUs. Saturated pixels are counted in the original raw flat field exposures before any processing (including bias subtraction), and excluding the overscan regions. The total number of saturated pixels is divided by the total number of pixels examined in all input raw frames, and the result is multiplied by 100.

**QC FLAT EFF:** Flat field lamp efficiency. *Units*: ADU/s

The efficiency is computed as the median of all pixels of the first input raw frame (bias subtracted), divided by its exposure time.

**QC FLAT PHN:** Photon noise in master screen flat field. *Units*: ADU

The photon noise is estimated in the following way: the difference frame between the first two input raw flat field frames is determined for their central 100x100 region. The standard deviation of all pixels of this difference frame is computed, and then divided by  $\sqrt{2N}$  where *N* is the total number of raw flat field frames contributing to the master flat field. The RON contribution is considered negligible.

**QC FLAT FPN:** Fixed-pattern noise. *Units*: ADU

The FPN is estimated in the following way: The difference of two 100x100 sub-frames of the same master flat field image is determined. The first subframe is extracted at the frame center, while the second is extracted from a position shifted by 10 pixels in the increasing X- and Y-directions. The standard deviation of the difference frame, divided by  $\sqrt{2}$ , minus the photon noise QC FLAT PHN (geometrically subtracted) yields the fixed-pattern noise. The RON is considered negligible in the computation of FPN.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	56 of 132

**QC FLAT FPN REL:** Relative fixed-pattern noise. *Units: none*

This quantity is the fixed pattern noise (QC FLAT FPN) divided by the median illumination level of the flat field exposure.

**QC FLAT CONAD:** Conversion factor from ADU to electrons. *Units:  $e^-$ /ADU*

If the exposure time of the first two input raw screen flat fields in the input set of frames is the same (within 4%), the absolute difference frame is computed. At each pixel the difference frame is divided by 2 and by the signal of the first frame. This frame estimates the gain (in  $\text{ADU}/e^-$ ) at each pixel, and the conversion factor is computed as the reciprocal mean of this frame.

**QC FLAT CONADERR:** Error on conversion factor from ADU to electrons. *Units:  $e^-$ /ADU*

This quantity is computed as the standard deviation of the gain frame, also used for the computation of QC FLAT CONAD, multiplied by QC FLAT CONAD squared.

### 9.3 efosc\_img\_sky\_flat

The EFOSC pipeline recipe *efosc\_img\_sky\_flat* is used to create a twilight master calibration frame from a set of raw twilight sky exposures. In order to eliminate the contributions of field stars on the jittered sequence of flat fields, the frame combination method must be based on a rejection algorithm (rather than on a simple average)<sup>15</sup>. The overscan regions, if present, are removed from the result.

#### 9.3.1 Input files

**SKY\_FLAT\_IMG:** *required* set of raw, unprocessed sky flat field frames.

**MASTER\_BIAS:** *required* master bias frame. Just one should be given.

#### 9.3.2 Output files

**MASTER\_SKY\_FLAT\_IMG:** Sky flat field master calibration frame.

Configuration parameters directly affecting this product are: *--stack\_method*.

#### 9.3.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_img\_sky\_flat* recipe will process the input frames.

*--stack\_method*: Frames combination method. *Default: median*

See explanation in recipe *efosc\_bias* configuration parameters (Section 9.1.3, page 52).

<sup>15</sup>Note that images are normalised to the same illumination level before applying the rejection algorithm.



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	57 of 132

### 9.3.4 Quality control parameters

Currently the following QC parameters, used by PSO and DPD, are evaluated by the *efosc\_img\_sky\_flat* recipe.

**QC OVEREXPO:** Percentage of overexposed pixels. *Units: none*

**QC SKYFLAT FLUX MIN:** Median level of dimmest input raw sky flat. *Units: ADU*

**QC SKYFLAT FLUX MAX:** Median level of brightest input raw sky flat. *Units: ADU*

## 9.4 efosc\_img\_science

The EFOSC pipeline recipe *efosc\_img\_science* is used to reduce a direct imaging scientific exposure. The bias master calibration is subtracted. The unbiased signal is then divided by the normalised sky flat field, and the overscan regions, if present, are removed from the result. The calibrated image is finally sent to a source detection and extraction application (SExtractor 2.5.0 [21]).<sup>16</sup>

### 9.4.1 Input files

**SCIENCE\_IMG:** *required* direct imaging scientific exposure.

**MASTER\_BIAS:** *required* bias master calibration frame.

**MASTER\_SKY\_FLAT\_IMG:** *required* sky flat field master calibration frame (normalised or not).

### 9.4.2 Output files

**SCIENCE\_REDUCED\_IMG:** Reduced science image.

Configuration parameters directly affecting this product are: *--cr\_remove*.

**PHOT\_BACKGROUND\_SCI\_IMG:** Background map produced by SExtractor [21].

Configuration parameters directly affecting this product are: *--sex\_radius*.

**SOURCES\_SCI\_IMG:** List of detected sources, SExtractor's cut (uncensored). The content of this table exclusively depends on the SExtractor configuration parameters setting. Please refer to [20] and [22] for details.

Configuration parameters directly affecting this product are: *--sex\_config*, *--sex\_mag*, *--sex\_magerr*.

**OBJECT\_TABLE\_SCI\_IMG:** Detected sources and source properties used by the pipeline. This table is the result of a selection applied to the list of detected sources produced by SExtractor: objects with either status `FLAGS` different from zero, or negative SExtractor `FWHM_IMAGE`, or no computed magnitude, are excluded from the object table. In addition to that, only some of the sources parameters are carried over to the object table:

<sup>16</sup>SExtractor is included in the pipeline software package, and is installed automatically.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	58 of 132

<b>x:</b>	$x$ CCD position (baricenter) of detected object. Identical to SExtractor parameter X_IMAGE.
<b>y:</b>	$y$ CCD position (baricenter) of detected object. Identical to SExtractor parameter Y_IMAGE.
<b>fwhm:</b>	Source width at half maximum, from gaussian fit. Identical to SExtractor parameter FWHM_IMAGE.
<b>a:</b>	Semi-major axis of object flux distribution, defined as max RMS of the object profile along any direction. Identical to SExtractor parameter A_IMAGE.
<b>b:</b>	Semi-minor axis of object flux distribution, defined as min RMS of the object profile along any direction. Identical to SExtractor parameter B_IMAGE.
<b>theta:</b>	Position angle between semi-major axis and the horizontal axis, counted counter-clockwise, in the domain $[-\pi/2, \pi/2[$ . Identical to SExtractor parameter THETA_IMAGE.
<b>ell:</b>	Derived as $1 - a/b$ .
<b>instr_mag:</b>	Instrumental magnitude, corresponding to the chosen SExtractor magnitude. As a default, identical to SExtractor parameter MAG_APER.
<b>dinstr_mag:</b>	Error on instrumental magnitude. As a default, identical to SExtractor parameter MAGERR_APER.
<b>class_star:</b>	Stellarity index, 1 = star, 0 = galaxy. Identical to SExtractor parameter CLASS_STAR.

Configuration parameters directly affecting this product are: `--sex_config`, `--sex_mag`, `--sex_magerr`.

### 9.4.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_img\_science* recipe will process the input frames.

`--extract_method`: Source extraction method. (**sex** = Use SExtractor, **test** = Test recipe *efosc\_img\_science*).  
*Default: sex*

The "test" method is just used to check that the recipe works properly on internal data, independently on external source detection and extraction programs such SExtractor. This is not interesting for the general user.

`--sex_exe`: Path to SExtractor executable. *Default: installation\_path/bin/sex*

This parameter can be changed in order to use other SExtractor installations, different from the one installed with the pipeline. In principle the pipeline should work also with previous (and likely future) SExtractor releases. This parameter could also be set to point to a user defined program, for example a script which calls SExtractor and then does some postprocessing of SExtractor's output before control is returned to the pipeline. The only requirement is that the specified command must behave like the SExtractor executable in terms of commandline parameters and output tables used by the pipeline.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	59 of 132

*--sex\_config*: Path to SExtractor configuration file. *Default: installation\_path/share/efosc/config/efosc.sex*

The SExtractor configuration file pointed by this parameter can be edited and modified, to control the way SExtractor operates. The SExtractor output parameters file, *efosc.param*, can also be found in the same directory: it is a list of the source parameters SExtractor would compute (and that would be written to the *SOURCES\_SCI\_IMG* table, see previous Section). No entries should be removed from this file, because the pipeline recipes rely on them: just new ones may be added. The parameter *--sex\_config* can also be changed in order to use SExtractor configuration files different from the one installed with the pipeline.

*--sex\_mag*: SExtractor magnitude used by recipe. *Default: MAG\_APER*

SExtractor computes instrumental magnitudes in different ways. Each computation method corresponds to one entry in the SExtractor output parameters file, *efosc.param* (see previous recipe parameter, *--sex\_config*): *MAG\_BEST*, *MAG\_AUTO*, *MAG\_ISO*, *MAG\_ISOCOR*, *MAG\_BEST*, are possible choices (see the SExtractor User's Guide [20] for details). The default is a simple aperture magnitude, *MAG\_APER*, where the aperture diameter (in pixel) is defined by the SExtractor configuration parameter *PHOT\_APERTURES*. To modify the monitored magnitude, ensure that the corresponding entry is present in the SExtractor output parameters file, *efosc.param*.

*--sex\_magerr*: SExtractor error on computed magnitudes. *Default: MAGERR\_APER*

The default is the error on the simple aperture magnitude, *MAG\_APER*.

*--sex\_radius*: Median filter radius for background map computation. *Default: 64* (unbinned pixels)

This parameter overwrites the value of the parameter *BACK\_SIZE* in the specified SExtractor configuration file (see recipe parameter *--sex\_config*).

*--cr\_remove*: Remove cosmic ray events from exposure. *Default: false*

Cosmic rays are detected and removed from image (by interpolation of surrounding pixels).

*This parameter is not active yet.*

#### 9.4.4 Quality control parameters

Currently the following QC parameters are evaluated by the *efosc\_science* recipe.

**QC SKYAVG**: Mean of sky background. *Units: mag/arcsec<sup>2</sup>*

The background determination is part of the source extraction algorithm (provided by SExtractor). This QC parameter is defined as  $M = -2.5 \log_{10}(F/A)$ , where  $F$  is the mean of the background map, and  $A$  the area of one image pixel in  $\text{arcsec}^2$ . Note that this is an instrumental magnitude, where neither color correction nor zeropoint is applied.

**QC SKYMED**: Median of sky background. *Units: mag/arcsec<sup>2</sup>*

The background determination is part of the source extraction algorithm (provided by SExtractor). This QC parameter is defined as  $M = -2.5 \log_{10}(F/A)$ , where  $F$  is the median of the background map, and  $A$  the area of one image pixel in  $\text{arcsec}^2$ . Note that this is an instrumental magnitude, where neither color correction nor zeropoint is applied.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	60 of 132

**QC SKYRMS:** Standard deviation of sky background. *Units:* mag/arcsec<sup>2</sup>

Standard deviation of the smoothed background level from its median value. The standard deviation is determined in term of flux (ADU/s) and then propagated to instrumental magnitude units. More specifically, if  $\Delta F$  is the variation of flux, the corresponding variation in magnitudes  $\Delta M$  is the differential of  $M = -2.5 \log_{10}(F/A)$ ,

$$\Delta M = -2.5 \frac{\Delta F}{F} \log_{10} e = 1.086 \frac{\Delta F}{F}$$

The background determination is part of the source extraction algorithm (provided by SExtractor).

**QC IMGQU:** Image quality of scientific exposure. *Units:* arcsec

Median FWHM (as computed by SExtractor) of stars detected on a calibrated scientific exposure. An object is considered a star if the corresponding SExtractor stellarity index is greater than 0.7 and the FWHM is larger than 1 pixel. *This is currently not working correctly.*

**QC IMGQUERR:** Uncertainty of image quality. *Units:* arcsec

Population standard deviation of the FWHM values obtained for each detected source from their median value (see parameter QC IMGQU).

**QC STELLAVG:** Mean stellarity index. *Units:* None

Mean SExtractor stellarity index of all objects used for QC IMGQU computation.

**QC IMGQUELL:** Mean star ellipticity. *Units:* None

Mean ellipticity of all objects used for QC IMGQU computation.

**QC IMGQUELLERR:** Standard deviation of star ellipticities. *Units:* None

Computed as 0.6745 times the median absolute deviation with respect to the median ellipticity of all objects used for QC IMGQU computation.

## 9.5 efosc\_zeropoint

The EFOSC pipeline recipe *efosc\_zeropoint* is used to estimate the atmospheric extinction from one imaging exposure on a photometric standard stars field.

The bias master calibration is subtracted from the raw exposure, and the median residual in the overscan regions is subtracted too. The unbiased signal is then divided by the normalised sky flat field produced by the recipe *efosc\_img\_sky\_flat*. The calibrated image is sent to a source detection and extraction application (SExtractor 2.5.0 [21]).<sup>17</sup> The detected sources are compared to a catalog of standard stars for identification. The recipe *efosc\_zeropoint* uses whatever catalog is specified in input, either Landolt's or Stetson's, or even both. If both catalogs are specified, they are merged before being used. In the merged catalog, if two stars are within 5 arcseconds they are considered identical and the one with the largest magnitude error is removed.<sup>18</sup> The comparison

<sup>17</sup>SExtractor is included in the pipeline software package, and is installed automatically.

<sup>18</sup>It should be noted that using simultaneously two different catalogs carries a significant risk to produce inconsistent results, as the magnitudes are not derived with the same method in both catalogs, and as a consequence common stars can differ by up to 0.2 magnitudes. The use of two catalogs is therefore strongly discouraged.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	61 of 132

Symbol	Definition	Unit
$M$	Catalog magnitude	mag
$C$	Catalog color	mag
$\Gamma$	Linear color correction term	
$M^*$	Color corrected catalog magnitude ( $M - \Gamma \cdot C$ )	mag
$g$	Detector gain	ADU/e <sup>-</sup>
$t$	Detector exposure time	s
$D$	Observed instrumental magnitude ( $-2.5 \log$ of counts)	mag
$m$	Corrected instrumental magnitude ( $D + 2.5 \log g + 2.5 \log t$ )	mag
$A$	Airmass	airmass
$E$	Atmospheric extinction coefficient	mag/airmass
$Z$	Zeropoint	mag

Table 9.5.1: Photometry related symbols used in this document. An index  $i$  may be added to indicate that a quantity refers to a specific star (for instance,  $M_i$  is the catalog magnitude of star  $i$ ), while an index  $j$  would refer to a specific frame (for instance,  $E_j$  is the atmospheric extinction related to frame  $j$ ). In the text the instrumental magnitude  $D$  is practically never used, and the exposure time and gain = 1 corrected magnitude  $m$  is used instead.

of observed vs catalog positions is made, whenever possible, applying point-pattern-matching techniques (described in detail in Section 10.6.6, page 116). If pattern matching either fails or is not applicable (e.g., too few standard stars are present in the field-of-view), then the stars identification will rely on the sky-to-CCD transformation specified in the input image FITS header (and if this transformation is incorrect no stars will be found, leading to an inevitable failure of the recipe). Finally, the atmospheric extinction  $E$  is estimated by optimally averaging the extinctions  $E_i$ , computed from each detected catalog star using the known values for the instrument zeropoint  $Z$  and the color filter correction  $\Gamma$ , applying the following formula:

$$E_i = \frac{Z + m_i - (M_i - \Gamma \cdot C_i)}{A}$$

(where higher order terms are neglected).<sup>19</sup> In order to directly evaluate both  $E$  and  $Z$  at least two different

<sup>19</sup>In the actual recipe implementation, the differences

$$Z_i = (M_i - \Gamma \cdot C_i) - (m_i - E_o A)$$

between the color corrected catalog magnitude and the corresponding instrumental magnitude corrected to airmass zero assuming an ideal atmospheric extinction coefficient  $E_o$ , are optimally averaged (see Section 10.2.2). The derived quantity is conventionally referred to as the *frame zeropoint*  $Z_{frame}$ . This way to proceed is quite misleading, because it conceals the fact that the zeropoint  $Z$  is a known constant of the instrument, while the variable term to determine is  $E$ , and not really  $Z$ . Such implementation is there for historical reasons: traditionally the frame zeropoint  $Z_{frame}$  is the Quality Control parameter used in the monitoring of the atmosphere quality. Now this has been adapted to a more physical view (see [28]): there was however no need to modify the old pipeline implementation, as the optimal estimate for the extinction coefficient  $E$  is related to the optimal estimate of the frame zeropoint  $Z$  by the

$$E = E_o + \frac{(Z - Z_{frame})}{A}$$

The assumptions on a photometric night atmospheric extinction  $E_o$  and instrument zeropoint  $Z$  are listed for each EFOSC filter in the photometric table (see Section 7.1, page 40).

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	62 of 132

exposures of standard star fields (not necessarily of the same field), obtained at (very) different airmasses, would be needed. This task is performed by the offline pipeline recipe *efosc\_photometry* (see Section 9.6, page 65).

### 9.5.1 Input files

**STANDARD\_IMG:** *required* photometric standard stars field exposure.

**MASTER\_BIAS:** *required* bias master calibration frame.

**MASTER\_SKY\_FLAT\_IMG:** *required* sky flat field master calibration frame (normalised or not).

**FLX\_STD\_IMG:** *required* photometric standard stars catalog (see Section 7.2, page 41).

**PHOT\_TABLE:** *required* photometric table (see Section 7.1, page 40).

### 9.5.2 Output files

**STANDARD\_REDUCED\_IMG:** Reduced standard stars field image.

Configuration parameters directly affecting this product are: *none*.

**PHOT\_BACKGROUND\_STD\_IMG:** Background map produced by SExtractor.

Configuration parameters directly affecting this product are: *--sex\_radius*.

**SOURCES\_STD\_IMG:** List of detected sources, SExtractor's cut (uncensored). The content of this table exclusively depends on the SExtractor configuration parameters setting. Please refer to [20] and [22] for details.

Configuration parameters directly affecting this product are: *--sex\_config*, *--sex\_mag*, *--sex\_magerr*.

**ALIGNED\_PHOT:** Detected sources and source properties selected by the pipeline, with zeropoint estimate for each object identified as a standard star. This table is an expansion of the OBJECT\_TABLE\_SCI\_IMG table produced by the recipe *efosc\_img\_science* (see Section 9.4.2, page 57). To the columns contained in the OBJECT\_TABLE\_SCI\_IMG, the following columns are added:

**instr\_cmag:** Instrumental magnitude, corrected to detector gain = 1 (electrons), unit time (flux), and airmass zero (assuming a photometric night atmospheric extinction  $E_o$  reported in the input PHOT\_TABLE). This quantity is computed as

$$m - E_o A = D + 2.5 \log g + 2.5 \log t - E_o A$$

**dinstr\_cmag:** Error on corrected instrumental magnitude.  
**object:** Name of identified standard star (from the input catalog).  
**ra:** Right Ascension of identified standard star (from the input catalog).  
**dec:** Declination of identified standard star (from the input catalog).

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	63 of 132

<b>mag:</b>	Color corrected catalog magnitude ( $M^*$ ).
<b>dmag:</b>	Error on color corrected catalog magnitude ( $\Delta M^*$ ).
<b>cat_mag:</b>	Catalog standard star magnitude ( $M$ ).
<b>dcat_mag:</b>	Error on catalog magnitude ( $\Delta M$ ).
<b>color:</b>	Color index of standard star ( $C$ ), chosen as in Section 7.1, page 40.
<b>dcolor:</b>	Error on color index ( $\Delta C$ ).
<b>cov_catm_col:</b>	Covariance of catalog magnitude and color (needed for error propagation).
<b>use_cat:</b>	Use (1) or do not use (0) the flagged standard star in recipe <i>efosc_photometry</i> . The recipe <i>efosc_zeropoint</i> will always set this flag to 1, but the user has the possibility to exclude any star from further processing.
<b>shift_x:</b>	Horizontal offset (in pixels) of identified standard star from expected position computed using the sky-to-CCD transformation of the input image.
<b>shift_y:</b>	Vertical offset (in pixels) of identified standard star from expected position computed using the sky-to-CCD transformation of the input image.
<b>zeropoint:</b>	Star zeropoint ( $Z$ ), computed as <b>mag - instr_cmag</b> , that is

$$Z = M^* - m + E_oA$$

<b>dzeropoint:</b>	Error on star zeropoint ( $\Delta Z$ ).
<b>weight:</b>	This number is related to the importance given to each computed star zeropoint in the computation of the optimally averaged zeropoint. Some of the weights might be negative, because the errors on individual zeropoints are correlated (if the covariance matrix is not diagonal the optimal weights are no longer the inverse of the variance, and some may happen to be negative: see Sections 10.2.1 and 10.2.2 for a mathematical treatment of this problem).

Configuration parameters directly affecting this product are: *--sex\_config*, *--sex\_mag*, *--sex\_magerr*.

### 9.5.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_zeropoint* recipe will process the input frames.

*--extract\_method*: Source extraction method. (**sex** = Use SExtractor, **test** = Test recipe *efosc\_zeropoint*). *Default: sex*

*--sex\_exe*: Path to SExtractor executable. *Default: installation\_path/bin/sex*

*--sex\_config*: Path to SExtractor configuration file. *Default: installation\_path/share/efosc/config/efosc.sex*

*--sex\_mag*: SExtractor magnitude used by recipe. *Default: MAG\_APER*

*--sex\_magerr*: SExtractor error on computed magnitudes. *Default: MAGERR\_APER*

*--sex\_radius*: Median filter radius for background map computation. *Default: 64 (unbinned pixels)*

The above configuration parameters are in common with the recipe *efosc\_img\_science*. They are explained in Section 9.4.3, page 58. Further parameters of recipe *efosc\_zeropoint* are:



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	64 of 132

**--ncat:** Number of catalog stars to use in pattern matching. *Default:* 10

A limited number of catalog stars (ideally, just 3) can be used to define a pattern to be searched within the position distribution of the detected objects. The sky-to-CCD transformation associated to the imaging exposure is used to select from the input catalog the stars that are expected to be found in the field-of-view. The parameter **--ncat** specifies how many of these stars should be used to compose a pattern. The stars are selected starting from the brightest ones. See Section 10.6.6, page 116 for a detailed description of the pattern-matching algorithm.

**--nsource:** Number of detected sources for each entry in pattern. *Default:* 15

The point-pattern made of selected catalog stars (see parameter **--ncat**) must be searched among the detected objects. Typically there are hundreds of detected objects available, and to perform all possible comparisons would require a long execution time (with no real improvement of the final result). Therefore just a subset of detected object (starting from the brightest ones) needs to be selected for pattern comparison. The parameter **--nsource** controls how many detected objects should be selected for matching. The number of selected objects is given by

$$N = nsource \cdot ncat$$

As a default,  $nsource = 15$  and  $ncat = 10$ , so 150 detected objects would be used in the pattern recognition process.

Once the pattern is recognised, an improved transformation from catalog to CCD positions can be determined, and all the standard stars in the field of view can be safely identified. In other words, setting the parameters **--nsource** and **--ncat** does not limit the actual number of standard stars that can be finally identified.

**--kappa:** Number of sigmas in triangular pattern scale and angle rejection. *Default:* 5.0 sigma

Pattern matching is the result of several triangles comparisons (see details in Section 10.6.6, page 116). When similar triangles are found, the corresponding rotation angle and scale ratio can be determined. In the determination of the mean transformation, angles and scales that deviate more than the specified number of sigmas are excluded and the process iterated till convergence is reached.

**--search:** Start search radius applied to find standard stars in field of view. *Default:* 20 pixel

No matter whether pattern matching was successful or not, the catalog sky positions are converted into CCD expected positions for each standard star. If pattern matching was successful, the sky-to-CCD transformation would be corrected by mean offset, angle, and scale, before being applied. The *search* parameter indicates what the search radius for a given star around its expected CCD position.

**--maxsearch:** Max search radius applied to find standard stars in field of view. *Default:* 20 pixel

If no sources are found applying the initial search radius, the search radius is increased by steps of 5 pixels till the maximum radius specified by this parameter

**--magcutE:** Expected max systematic error. *Default:* 1.0 mag

This threshold is applied in zeropoint computation. Any individual (star) zeropoint which deviates from the best estimate by more than the specified threshold is excluded, and the zeropoint estimation is iterated. The sense of this parameter is that any deviation higher than specified should be interpreted as an object misidentification (since it couldn't possibly be explained by a systematic error in the determination of the color term).



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	65 of 132

--*magcutk*: Number of sigmas in individual zeropoint rejection. *Default*: 5.0 sigma

This threshold is applied in zeropoint computation, after the *magcutE* screening, and it deals with purely statistical errors. Any individual (star) zeropoint which deviates from the best estimate by more than the specified number of sigmas is excluded, and the zeropoint estimation is iterated. The sense of this parameter is that any deviation higher than specified should be interpreted as zeropoint miscalculation due to unexpected effects (such as imperfections of the detector), as it could hardly be explained by random error.

### 9.5.4 Quality control parameters

Currently the following QC parameters are evaluated by the *efosc\_zeropoint* recipe.

**QC ZPOINT:** Frame zeropoint ( $Z_{frame}$ ). *Units*: mag

See subsections of 9.5 above, and Section 10.2 on page 100.

**QC ZPOINTRMS:** Uncertainty of frame zeropoint. *Units*: mag

This is the expected random statistical error propagated from both observed and catalog quantities (see Section 10.2, page 100).

**QC ZPOINT NSTARS:** Number of stars used for zeropoint computation. *Units*: None

**QC EXTCOEFF:** Atmospheric extinction coefficient. *Units*: mag/airmass

Atmospheric extinction coefficient  $E$  required to explain the difference between  $Z_{frame} = \text{QC ZPOINT}$  and the nominal expected zeropoint  $Z$  given as input to the recipe, that is  $E = E_o + (Z - Z_{frame})/A$ , where  $A$  is the airmass, and  $E_o$  is the atmospheric extinction coefficient that was assumed for the computation of  $Z_{frame}$  (see begin of this Section, page 60).

**QC EXTCOEFFERR:** Error on atmospheric extinction coefficient. *Units*: mag/airmass

Error propagation on the computation of QC EXTCOEFF.

## 9.6 efosc\_photometry

This recipe is used for the processing of several ALIGNED\_PHOT tables produced by the recipe *efosc\_zeropoint*, enabling the estimation of quantities such as the best atmospheric extinction and linear color correction terms related to a filter. In particular it enables accurate photometry by determining, from ALIGNED\_PHOT tables derived from a set of dithered (rotated, translated) exposures of a photometric standard star field, a correction map relative to a given flat field frame (the same used in the *efosc\_zeropoint* processing). This method is described in [28].

The general model for the corrected instrumental magnitude  $m_{ij}$  of star  $i$  on exposure  $j$  is

$$m_{ij} = M_i - \Gamma \cdot C_i + p(A_j, C_i) + E_j A_j - Z + f(x_{ij}, y_{ij})$$

where the symbols are consistent with table 9.5.1 (page 61), and  $x$  and  $y$  are detector coordinates in pixel. All quantities are referred to the  $i$ -th star in the  $j$ -th exposure as indicated. Non-linear dependencies are accounted for by the functions  $p()$  and  $f()$ .

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	66 of 132

In the *efosc\_photometry* implementation  $p()$  is a  $d$ -order polynomial with zero and first order terms set to zero, that is:

$$p(A, C) = \sum_{r=2}^d \sum_{k=0}^r p_{k,r-k} C^k A^{r-k}$$

The lower order terms are redundant, as  $p_{00}$  would be the zeropoint,  $p_{01}$  the atmospheric extinction  $E$ , and  $p_{10}$  the linear color correction term  $\Gamma$ , which are already explicit in the general equation.

Also  $f()$  is a polynomial modeling of the deviations which may be present in the used sky flat field.<sup>20</sup> In this polynomial only the constant term is set to zero:

$$f(x, y) = \sum_{r=1}^d \sum_{k=0}^r f_{k,r-k} x^k y^{r-k}$$

The constant term is redundant, as  $f_{00}$  would be degenerate with  $M_i$ .

Substituting  $M_i - \Gamma \cdot C_i = M_i^*$  the general equation becomes

$$m_{ij} = M_i^* + p(A_j, C_i) + E_j A_j - Z + f(x_{ij}, y_{ij})$$

The *efosc\_photometry* recipe can solve this system of equations by leaving fixed or fitting any of the parameters detailed below:

- $M_i^*$  It can be fixed or free for each individual star. For the  $i$ -th star, if the corresponding entry in the USE\_CAT column of the input ALIGNED\_PHOT table is set to 1,  $M_i$  and  $C_i$  are fixed to the catalog values (i.e.,  $M_i^*$  is fixed); otherwise the color corrected magnitude,  $M_i^*$ , is determined ( $M_i^*$  is free). Since only relative magnitudes can be measured, the magnitude of at least one star must be assumed; this defines the overall scale of the measured magnitudes (see below).
- $\Gamma$  The color term can be a free parameter if two or more  $M_i$  and  $C_i$  are provided (i.e., if two or more  $M_i^*$  are fixed). Physically, this corresponds to determining the color term by comparing the instrumental magnitudes of a star with known color to its physical magnitude; however, the magnitude of one more star must be provided in order to define the overall zeropoint.
- $Z$  The instrument zeropoint can be determined, if it is not attempted to fit at the same time an atmospheric extinction for each available frame.
- $E_j$  The atmospheric extinction coefficient can be determined for each frame if the instrument zeropoint  $Z$  is fixed. It is also possible to fit a single  $E$  valid for all frames, or one  $E$  for each group of frames belonging to the same night: in such cases,  $Z$  can be a free parameter.
- $f, p$  The number of free parameters are determined by the user specified degrees of the polynomial. For example, if both degrees are set to zero, the sums would be empty and there will be no polynomial coefficients to fit. It is not possible for the user to provide as input certain (fixed) values of the polynomial coefficients. To

<sup>20</sup>This implies that the input ALIGNED\_PHOT tables must all be produced by recipe *efosc\_zeropoint* runs where the same flat field correction was applied.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	67 of 132

achieve the same effect, a corrected master flat field can be used in *efosc\_zeropoint* to compute the ALIGNED\_PHOT tables.

Note that the degeneracy between constant terms is handled here by setting  $f_{oo} = 0$  and  $M_o^* = M_o$ , unlike in [28] where  $M_o^* = Z = 0$  is set. Note also that some combinations (such as fitting  $E_j$  for each input ALIGNED\_PHOT table along with  $Z$ ) do not make sense and are not allowed. The errors of  $g_j$  and  $t_j$ , used in the computation of  $m_{ij}$  (see table 9.5.1, page 61), are not propagated because they are usually insignificant in the overall error budget, and not readily available.

The method described in [28] Appendix A corresponds to the following configuration:

$M_i^*$  free  
 $\Gamma$  fixed  
 $Z$  fixed  
 $E_j$  all free, but same value for same nights  
 $f$  non-zero order,  $d$   
 $p$  zero order (no free parameters)

The method described in [28] Appendix B corresponds to

$M_i^*$  fixed  
 $\Gamma$  free  
 $Z$  free  
 $E$  one free parameter, valid for all frames  
 $f$  non-zero order,  $d$   
 $p$  second order (one free parameter)

For a more detailed description of the determination of the model's free parameters, see the Section 10.3, page 106.

The *efosc\_photometry* implementation identifies common stars in different frames by their celestial coordinates (RA, Dec). Therefore both standard and non-standard stars can be used in the model fitting. However, if fitting  $f$  is not requested, only standard stars will be actually processed by the recipe.

### 9.6.1 Input files

**PHOT\_TABLE:** *required* photometric table, containing atmospheric extinction coefficients for each filter (see Section 7.1, page 40).

**ALIGNED\_PHOT:** *required* set of one or more tables of detected sources, as produced by the recipe *efosc\_zeropoint*.

**MASTER\_SKY\_FLAT\_IMG:** *required* sky flat field master calibration frame as produced by the recipe *efosc\_img\_sky\_flat*. In case the fitting of  $f$  is requested, it should be the same frame used in *all* the runs of *efosc\_zeropoint* which produced the input ALIGNED\_PHOT tables.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	68 of 132

## 9.6.2 Output files

**PHOT\_COEFF\_TABLE:** A one row table with (potentially) the same columns as the PHOT\_TABLE (see Section 7.1, 40):

<b>filter:</b>	Name of filter
<b>ext:</b>	Created only if <i>one</i> extinction is fitted
<b>dext:</b>	Created only if <i>one</i> extinction is fitted
<b>col:</b>	Created only if the color term is fitted
<b>dcol:</b>	Created only if the color term is fitted
<b>zpoint:</b>	Created only if the instrumentzeropoint is fitted
<b>dzpoint:</b>	Created only if the instrumentzeropoint is fitted

If neither one of  $E$ ,  $\Gamma$  and  $Z$  are fitted, this table is not created.

**EXTINCTION\_PER\_NIGHT:** List of atmospheric extinction coefficients per night. This table is only produced if an individual extinction for each night in the input set of frames is fitted, and it has the following structure:

<b>filename:</b>	Name of input PHOT_TABLE
<b>ext:</b>	Atmospheric extinction (mag/airmass)
<b>dext:</b>	Error on atmospheric extinction (mag/airmass)
<b>mjd-night:</b>	Night (unique) identifier (integer MJD)

**EXTINCTION\_PER\_FRAME:** List of atmospheric extinction coefficients per input frame. This table is only produced if an individual extinction for each one of the input frames is fitted, and it has the following structure:

<b>filename:</b>	Name of input PHOT_TABLE
<b>ext:</b>	Atmospheric extinction (mag/airmass)
<b>dext:</b>	Error on atmospheric extinction (mag/airmass)
<b>mjd-obs:</b>	MJD of observation

**CORRECTION\_MAP:** Flat field correction map (magnitude), the evaluation of  $f$  at each pixel. This is only produced if the correction  $f$  is requested.

Configuration parameters directly affecting this product are: *all*.

**CORRECTION\_FACTOR:** Flat field correction map (flux). The input flat field must be multiplied by this map in order to produce the corrected flat field. This is only produced if the correction  $f$  is requested.

Configuration parameters directly affecting this product are: *all*.

**MASTER\_FLAT\_IMG:** Corrected flat field. This is only produced if the correction  $f$  is requested.

Configuration parameters directly affecting this product are: *all*.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	69 of 132

### 9.6.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_photometry* recipe will process the input files.

--fitz: Fit the instrument zeropoint ( $Z$ ). *Default: true*

If set to false, the zeropoint  $Z$  read from the input PHOT\_TABLE is assumed.

--fit\_all\_mag: Fit star magnitudes ( $M_i^*$ ). *Default: false*

If set to true, all magnitudes are fitted. If set to false, all magnitudes are fixed, unless the corresponding entry in the USE\_CAT column of the input ALIGNED\_PHOT table is set to 0 (meaning "do not use this catalog magnitude"). In either case, there is no effect on the magnitude of the first standard star in the first input table, which remains frozen by definition to its catalog value (even if USE\_CAT is set to 0).

--fite: Fit atmospheric extinction coefficient ( $E$ ). (**no** = don't fit any, **one** = fit one extinction for all, **pernight** = fit an extinction for each night, **perframe** = fit an extinction for each input frame). *Default: pernight*

If set to **no**, the atmospheric extinction  $E_o$  read from the input PHOT\_TABLE is assumed. The option **one** would fit just one mean atmospheric extinction for all frames. Choosing **pernight** would fit an independent atmospheric extinction for each night found in the input dataset. When choosing **perframe**, it would be appropriate to set --fitz to "false", or the fit will likely fail (this holds also in the **pernight** case, if only one frame per night is available). Trying to fit any atmospheric extinction when all input tables include only sources from the same airmass, would also lead to a failure.

--fitc: Fit linear color correction term ( $\Gamma$ ) *Default: false*

If set to true, the linear color correction term is fit. If set to false, the linear color correction term read from the input PHOT\_TABLE is assumed.

--degreef1: Correction map polynomial degree *Default: 0*

--degreef2: Correction map polynomial degree *Default: -1*

Degree and type of the  $f$  correction polynomial: if both degrees are positive numbers the matrix of polynomial coefficients is rectangular (*degreef1* is related to  $x$  and *degreef2* to  $y$  directions), while if *degreef2* is negative the coefficients matrix is triangular of size *degreef1*. *degreef1* = 0 disables the fitting of the  $f$  correction, and in this case only standard stars are involved in the fitting procedure.

--degreep: Polynomial degree of non linear color correction. *Default: 0*

Degree of the  $p$  polynomial accounting for non-linear dependencies from color and airmass. *degreep* = 0 disables the fitting of the  $p$  correction.

### 9.6.4 Quality control parameters

Currently the following QC parameters are evaluated by the *efosc\_photometry* recipe. See subsections of 9.6 above, and Section 10.3 on page 106 for more details on how they are computed.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	70 of 132

**QC INSTRUMENT ZEROPOINT:** Instrumentzeropoint. *Units:* mag

This is the *true* instrumentzeropoint  $Z$  (different from the one computed by recipe *efosc\_zeropoint*, see Section 9.5, page 60). This quantity is computed only if *-fitz=true*.

**QC INSTRUMENT ZEROPOINT ERROR:** Error on instrumentzeropoint. *Units:* mag

This is the expected random statistical error propagated from both observed and catalog quantities.

**QC ATMOSPHERIC EXTINCTION:** Atmospheric extinction coefficient. *Units:* mag/airmass

This is the (mean) atmospheric extinction, valid for all input frames. This quantity is computed only if *-fite = one*.

**QC ATMOSPHERIC EXTINCTION ERROR:** Error on atmospheric extinction. *Units:* mag/airmass

This is the expected random statistical error propagated from both observed and catalog quantities.

**QC COLOR CORRECTION:** Linear color correction term. *Units:* none

This quantity is computed only if *-fitc=true*.

**QC COLOR CORRECTION ERROR:** Error color correction term. *Units:* none

This is the expected random statistical error propagated from both observed and catalog quantities.

## 9.7 efosc\_calib

This recipe identifies reference lines on MOS arc lamp exposures, and traces (if available) the spectral edges on the associated flat field exposures. With this information the spectral extraction mask to be applied in the scientific data reduction is determined. From the input flat field exposures a normalised flat field frame is also derived.

The input arc lamp and flat field exposures are assumed to be obtained quasi-simultaneously, so that they would be described by exactly the same optical and spectral distortions.

### 9.7.1 Input files

In alphabetical order:

**GRISM\_TABLE:** *optional* grism table. This table defines a subset of recipe configuration parameters controlling the way spectra are extracted for any particular grism. A set of standard grism tables is provided with the pipeline (see Section 7.3, page 43 for details).

**LAMP\_MOS:** *required* raw arc lamp spectrum exposure. Just one frame should be specified.

**MASTER\_BIAS:** *required* master bias frame. Just one should be given. Alternatively, it is possible to specify a set of raw, unprocessed bias frames (DO category: BIAS): in this case the input BIAS frames are used for the creation of an internal median MASTER\_BIAS frame, that is finally added to the recipe products for further use by other recipes.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	71 of 132

**LINE\_CATALOG:** *required* line catalog. It must contain the reference wavelengths (in Ångstrom) for the arc lamp used. The only requirement for this table is to contain a column listing such wavelengths, whose name may be specified using the configuration parameter `--wcolumn` (see Section 9.7.3, page 80). A standardline catalog is also provided with the pipeline for each EFOSC2 grism (see Section 7 for details).

**SCREEN\_FLAT\_MOS:** *required* raw spectral screen flat exposure. If more than one is provided, the input frames are stacked into one.

## 9.7.2 Output files

Not all output frames listed here are always produced. Some of them are created only on request (see Section 9.7.3, page 80), and some other are never created in case of long-slit data. Here is the list of all the possible output frames, in alphabetical order, together with a list of related configuration parameters.<sup>21</sup>

**CURV\_COEFF\_MOS:** table containing the coefficients of the spatial curvature fitting polynomials. This table is not produced in case long-slit data. The table columns are the following:

**slit\_id:** Slit identification number (see the `SLIT_LOCATION_MOS` entry for a definition of the *slit\_id*). Each identification appears twice, in consecutive rows: the top row refers to the left flat field spectrum edge, the bottom row to its right edge.

**c0, c1, c2, ...:** Curvature coefficients, depending on the degree of the fitting polynomial.

Configuration parameters directly affecting this product are `--cdegree` and `--cmode`.

Configuration parameters having significant impact are `--startwavelength` and `--endwavelength`.

**CURV\_TRACES\_MOS:** table containing the *x* CCD positions of the detected spectral edges at different *x* CCD positions. This table is not produced in case of long-slit data. The table columns are the following:

**x:** *y* CCD positions.

**t<slit\_id>:** *x* CCD positions of the flat spectrum left edge from slit *slit\_id* (for the definition of *slit\_id* see the `SLIT_LOCATION_MOS` entry).

**b<slit\_id>:** *x* CCD positions of the flat spectrum right edge from slit *slit\_id*.

**t<slit\_id>\_mod:** Modeling of the flat spectrum left edge from slit *slit\_id*.

**b<slit\_id>\_mod:** Modeling of the flat spectrum right edge from slit *slit\_id*.

**t<slit\_id>\_res:** Residuals of curvature fit of the flat spectrum left edge from slit *slit\_id*.

**b<slit\_id>\_res:** Residuals of curvature fit of the flat spectrum right edge from slit *slit\_id*.

Typical tracing residuals are not greater than 0.3 pixels (see Figure 9.7.6, page 83).

The traces of some edges may be missing because tracing is not always possible between spectra that are very close to each other. This does not prevent the final extraction of all the spectra, if a global spatial

<sup>21</sup> See Section 9.7.3, page 80, for a complete description of the recipe configuration parameters.



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	72 of 132

curvature model is applied by setting the configuration parameter `--cmode > 0`: but residuals cannot be evaluated in this case.

Note that in case of confusion between nearby spectra, where the exact position of the transition line between one spectrum and the other can be ambiguous, the position of the edge ideally traced by the global curvature model might not exactly correspond to the true (and not observable) spectral edge. It should be understood, however, that the aim of the computed model is primarily to eliminate the spatial curvature, and that this can be obtained without knowing the absolute positions of the traces. In summary, observing extracted spectra<sup>22</sup> that include signal from other spectra and/or extending beyond their true spatial extension, does not imply that the spatial curvature was not properly removed. As a matter of fact nearby spectra *do* sometimes contaminate each other physically, by actually mixing their signals (case of crossing edges). In case of doubt, the extracted spectra should be carefully examined and compared with the corresponding original spectra found in the CCD exposure, in order to set the configuration parameter `--cmode` as appropriately as possible.

The only real solution to this problem would be to design masks where spectra are always well separated from each other (a buffer zone of 3 or 4 pixels would be sufficient).<sup>23</sup>

Configuration parameters directly affecting this product are `--cdegree` and `--cmode`.

Configuration parameters having significant impact are `--startwavelength` and `--endwavelength`.

**DELTA\_IMAGE\_MOS:** deviation from the linear term of the wavelength calibration polynomials.

This image is used together with the `DISP_RESIDUALS_TABLE_MOS` to enable quality control of the obtained solutions (see Figure 9.7.1).

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--dispersion`, `--peakdetection`, `--wradius`, and `--wdegree`.

**DISP\_COEFF\_MOS:** table containing the wavelength calibration polynomial coefficients. This table contains as many rows as in the `REDUCED_LAMP_MOS` image, ordered in the same way. The table columns are the following:

<b>c0, c1, c2, ...:</b>	Model coefficients, depending on the degree of the fitting polynomial.
<b>nlines:</b>	Number of identified reference lines used in the fit.
<b>error:</b>	Model mean accuracy computed from the observed fit residuals, keeping into account the number of model free parameters and the number of available reference lines:

$$\sigma = \sigma_{res} \sqrt{\frac{(n+1)}{N}}$$

where  $\sigma_{res}$  is the standard deviation of the residuals,  $n$  the polynomial degree, and  $N$  the total number of reference lines used in the fit. This evaluation of the

<sup>22</sup>See entry `REDUCED_LAMP_MOS` in this Section, or entries `MAPPED_SCI_MOS` and `MAPPED_ALL_SCI_MOS` on page 90.

<sup>23</sup>It may be pointed out that this problem would "easily" be solved by applying an accurate physical model of the instrument. This however would be possible only under the assumption of a perfectly stable instrument, a dream that – together with the availability of the accurate physical model – remains too often unfulfilled.



ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	73 of 132

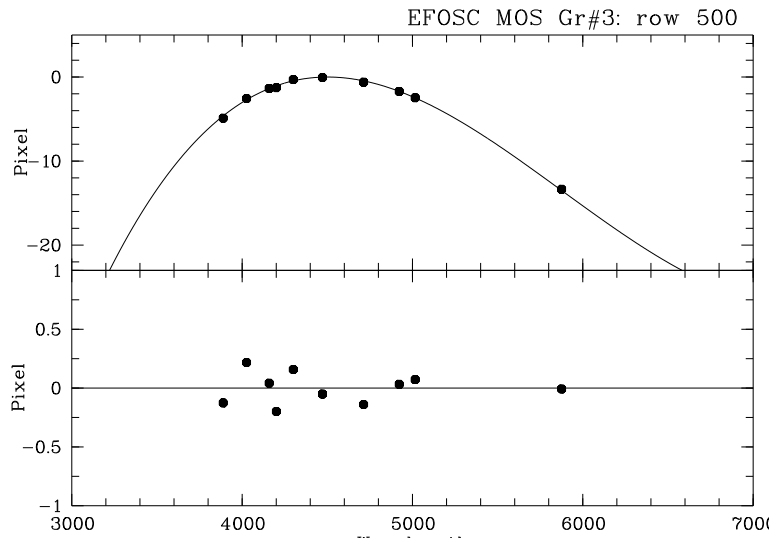


Figure 9.7.1: *Top panel: deviation of the identified peaks from the linear term of the 500th fitting polynomial (column d500 of the `DISP_RESIDUALS_TABLE_MOS`). The solid line is the polynomial model with the linear term subtracted, drawn from row 500 of the `DELTA_IMAGE_MOS` product. Bottom panel: fit residuals of the identified peaks (identical to the residuals recorded at row 500 of the `DISP_RESIDUALS_MOS` image).*

model accuracy makes sense only in absence of systematic trends in the residuals shown in the `DISP_RESIDUALS_MOS` image, and only under the assumption that data are not overfitted (i.e., the degree of the fitting polynomial is not higher than necessary, or practically speaking is the lowest capable of eliminating systematic trends in the residuals). Typical values of the model accuracy range between 0.05 and 0.1 pixels as confirmed by simulations.

Configuration parameters directly affecting this product are `--wdegree`, `--wmode` and `--wmosmode`.

Configuration parameters having significant impact are `--dispersion`, `--peakdetection`, `--wradius`, `--wreject`, `--startwavelength` and `--endwavelength`.

**DISP\_RESIDUALS\_MOS:** residuals of each wavelength calibration fit (in pixels). This image is only created if the `--check` configuration parameter is set. The residuals of the derived wavelength calibration with respect to the measured pixel positions of the reference arc lamp lines are collected in this image, with  $x$  pixels corresponding to the original  $y$  CCD pixels, and  $y$  pixels corresponding to the `REDUCED_LAMP_MOS` pixels (i.e., to the rectified spatial coordinate, see figure 9.7.2). Typical observed residuals should be around 0.2 pixels.<sup>24</sup> Note that all residuals are shown, including those from lines which were excluded from the polynomial fit, i.e., residuals larger than the threshold specified with the configuration parameter `--wreject` (see Section 9.7.3, page 80).

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--dispersion`, `--peakdetection`, `--wradius`, and `--wdegree`.

<sup>24</sup>This is the accuracy of a single peak position measurement, not the accuracy of the model of course...

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	74 of 132

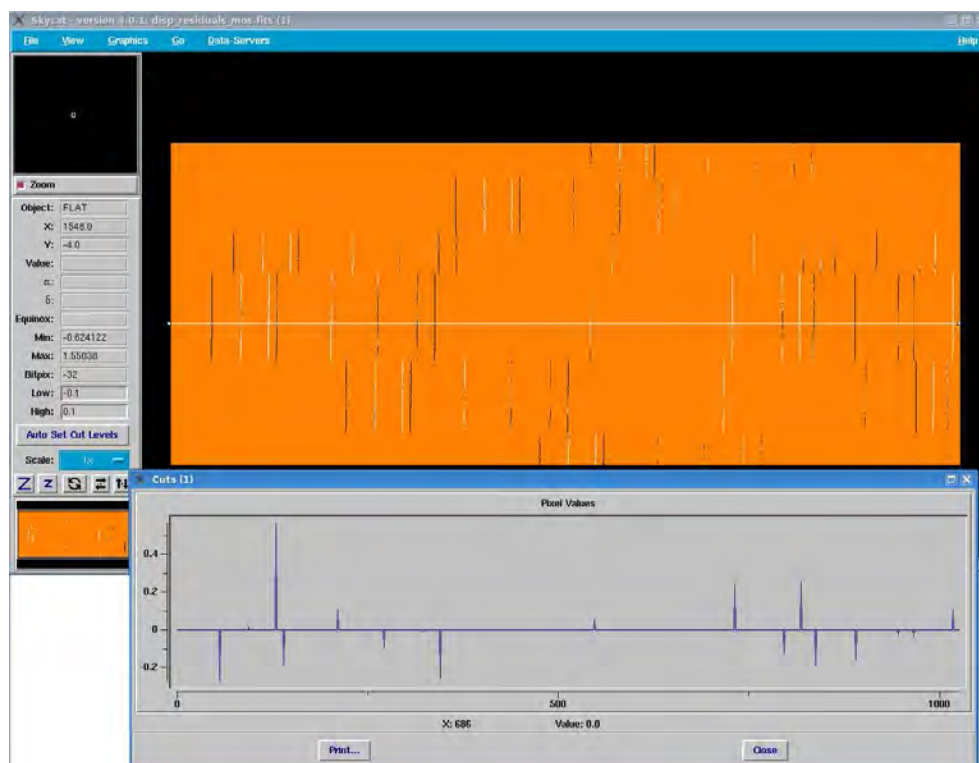


Figure 9.7.2: *DISP\_RESIDUAL\_MOS* from an arc lamp calibration with grism #11. In the foreground is a plot of the residuals from one image row.

**DISP\_RESIDUALS\_TABLE\_MOS:** table containing different kinds of residuals of a sample of wavelength calibration fits. Note that all residuals are shown, including those from lines that were excluded from the polynomial fit, i.e., residuals larger than the threshold specified with the configuration parameter *--wreject* (see Section 9.7.3, page 80). Just one every 10 of the polynomial fits listed in the *DISP\_COEFF\_MOS* table are examined. For an overview of all the polynomial fits residuals see the *DISP\_RESIDUALS\_MOS* image.

The residuals table columns are the following:

- wavelength:** Wavelengths of the reference lines (see entry *LINE\_CATALOG*).
- r<row>:** Fit residuals of the identified peaks (in CCD pixel). *row* is the number of the examined row of the *DISP\_COEFF\_MOS* table.
- d<row>:** Deviation of the identified peaks from the linear term of the fitting polynomial (in CCD pixel). This can be compared with the corresponding row of the *DELTA\_IMAGE\_MOS* product (see Figure 9.7.1).
- p<row>:** *y* pixel position of reference lines on CCD.

Configuration parameters directly affecting this product are *--startwavelength* and *--endwavelength*.

Configuration parameters having significant impact are *--dispersion*, *--peakdetection*, *--wradius*, and *--wdegree*.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	75 of 132

**GLOBAL\_DISTORTION\_TABLE:** table containing the modeling of the coefficients of the local distortion models listed in the `DISP_COEFF_MOS` and the `CURV_COEFF_MOS` tables. It is produced only if the configuration parameter `--slit_ident` is set, and at least 6 spectra are found on the CCD. This table is currently used for quality control, and to support the on-line quick-look scientific data reduction. See Section 7 for more details.

**MAPPED\_NORM\_FLAT\_MOS:** rectified and wavelength calibrated normalised screen flat field image (see entry `MASTER_NORM_FLAT_MOS` in this Section). This is the result of applying the extraction mask derived from the flat field and arc lamp exposures to the normalised flat field frame itself. This image is typically used for instrument health monitoring. Its size is identical to the size of the `REDUCED_LAMP_MOS` image (see corresponding entry in this Section).

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--dispersion`, `--peakdetection`, `--wradius`, `--wdegree`, `--wmode` and `--wmosmode`.

**MAPPED\_SCREEN\_FLAT\_MOS:** rectified and wavelength calibrated master screen flat field image (see entry `MASTER_SCREEN_FLAT_MOS` in this Section). This is the result of applying the extraction mask derived from the flat field and arc lamp exposures to the master flat field frame itself. This image is typically used for instrument health monitoring. Its size is identical to the size of the `REDUCED_LAMP_MOS` image (see corresponding entry in this Section).

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--dispersion`, `--peakdetection`, `--wradius`, `--wdegree`, `--wmode` and `--wmosmode`.

**MASTER\_NORM\_FLAT\_MOS:** normalised flat field image, derived dividing the master screen flat by its smoothed version (see the smoothing configuration parameters description in Section 9.7.3, page 80). Comparing this image with the `MASTER_SCREEN_FLAT_MOS` may give an immediate feeling of the goodness of the computed curvature model used for the extraction of the normalised spectra.

Configuration parameters directly affecting this product are `--sdegree`, `--ddegree`, `--sradius`, `--dradius`, `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--cdegree` and `--cmode`.

**MASTER\_SCREEN\_FLAT\_MOS:** combined flat field image. It is the sum of all the input screen flat fields.

**REDUCED\_LAMP\_MOS:** rectified and wavelength calibrated arc lamp image (see Figure 9.7.3). This is the result of applying the extraction mask derived from the flat field and arc lamp exposures to the input arc lamp exposure itself. This image is just useful to get an immediate feeling of the goodness of the computed extraction mask. Note that this image is also bias and background subtracted. Its  $x$  size depends on the spectral extraction range ( $\lambda_{min}, \lambda_{max}$ ) and on the value used for the dispersion in wavelength units per pixel,  $D$ , defined by the configuration parameter `--dispersion` (see Section 9.8.3, page 93):

$$N_x = \text{floor}\left(\frac{\lambda_{max} - \lambda_{min}}{D}\right)$$

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	76 of 132

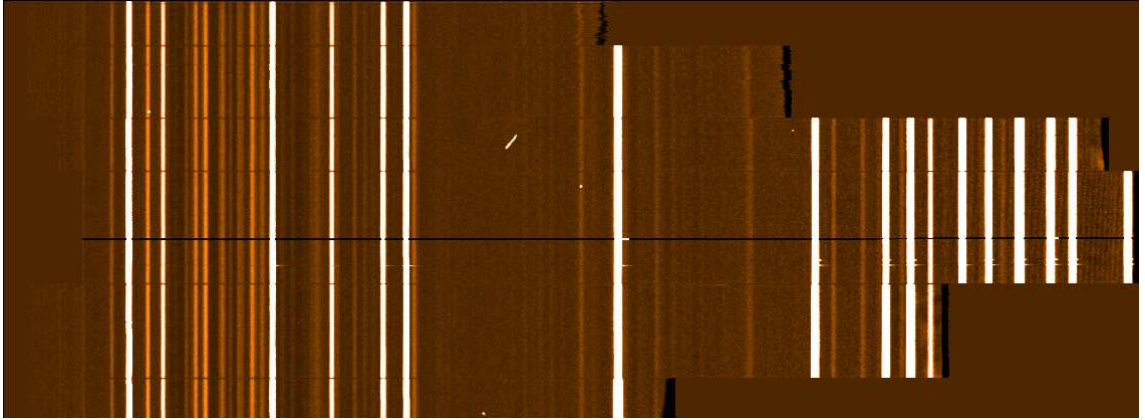


Figure 9.7.3: *REDUCED\_LAMP\_MOS* from an arc lamp exposure with grism #11.

The  $y$  size of this image matches the  $x$  size of the exposed part of the CDD in the case of long-slit data. In the case of multi-spectra observations the  $y$  size of this image is equal to the total number of spatially rectified pixels: each slit spectrum is extracted between the traces of its left and right edges (see products *CURV\_TRACES\_MOS* and *CURV\_COEFF\_MOS*), and spatially remapped into a constant number of pixels at each  $y$  CCD coordinate. The number of rectified pixels for the  $i$ -th slit spectrum is computed as

$$N_i = \text{ceil}(t_i - b_i) + 1$$

where  $t_i$  and  $b_i$  are the  $x$  CCD coordinates of the  $i$ -th slit spectrum edges at the position of the grism central wavelength.<sup>25</sup>  $N_i$  is increased by 1 to ensure a slight oversampling of the original signal. The total  $y$  size of the image is then given by

$$N_y = \sum_{i=0}^n N_i$$

where  $n$  is the number of extracted slit spectra. In case of generic MOS data the slit spectra are ordered from top to bottom as they appear from left to right on the CCD, and their positions are listed in the *SLIT\_LOCATION\_MOS* table. The wavelength of each image pixel can be computed using the *CRPIX1*, *CRVAL1* and *CDELTA1* FITS keywords:

$$\lambda = CDELTA1 \cdot (x - CRPIX1) + CRVAL1$$

where  $x$  is the pixel number counted from left starting from 1.

Note that resampling the original spectrum at a constant wavelength step introduces distortions of the signal, that depend on the original signal pixelisation on the CCD. This is a side-effect of interpolation, that tends to systematically overestimate and underestimate the interpolated value according to the position of the interpolation point with respect to the original CCD pixels.<sup>26</sup> This is especially evident in the case

<sup>25</sup>They correspond to the coefficients  $c0$  of the *CURV\_COEFF\_MOS* table, or to  $y_{top}$  and  $y_{bottom}$  in the *SLIT\_LOCATION\_MOS* table.

<sup>26</sup>No matter what interpolation method or kernel is chosen, this will always happen, unless the signal to resample is very well known in advance – which would make the interpolation pointless anyway: this would allow a perfect resampling of arc lamp spectra, for instance, but would not be applicable to scientific spectra.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	77 of 132

of long-slit data: even if the reference lines of the resampled spectra will appear perfectly straight on the rectified image, the signal level along an image column corresponding to an arc lamp reference line will appear to follow a wavy pattern. This makes apparent that the resampling of scientific data is not always acceptable (depending on the scientific aim of a specific observation program). A detailed analysis of the scientific signal should be based on the unbinned data matched with the corresponding wavelength map – see entry `WAVELENGTH_MAP_MOS`.

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--dispersion`, `--peakdetection`, `--wradius`, `--wdegree`, `--wmode` and `--wmosmode`.

**SLIT\_LOCATION\_MOS:** slit positions, both on the CCD and on the rectified image of the arc lamp exposure (`REDUCED_LAMP_MOS`). The slits are listed from top to bottom, according to their  $x$  position on the CCD, and they are identified by a *slit\_id* number. The *slit\_id* is derived from the FITS header of the input data, where the slits parameters are written to FITS keywords named

ESO INS MOS<slit\_id> <parameter>

For instance, the expected  $x$  position in pixels<sup>27</sup> of the third MOS slit is written to the FITS keyword:

ESO INS MOS3 POSX

The slit identification number is the <*slit\_id*> used in the naming convention for these keywords. The *slit\_id* in the above example is 3. Note that in the MOS case the *slit\_id* is identical to the slit sequence number in the left–right ordering of the spectra on the CCD.

The slits location table columns are the following:

<b>slit_id:</b>	Slit identification number
<b>xtop:</b>	$x$ CCD position of central wavelength from left end of slit.
<b>ytop:</b>	$y$ CCD position of central wavelength from left end of slit.
<b>xbottom:</b>	$x$ CCD position of central wavelength from right end of slit.
<b>ybottom:</b>	$y$ CCD position of central wavelength from right end of slit.
<b>position:</b>	First row of <code>REDUCED_LAMP_MOS</code> image containing the rectified slit spectrum bottom row. Image rows are counted from bottom, starting from 0.
<b>length:</b>	Number of rows in <code>REDUCED_LAMP_MOS</code> image including the slit spectrum.

If the slit identification task is not run (see configuration parameter `--slit_ident`, Section 9.8.3, page 93), or if the slit identification task fails (e.g., in the case of just two slits) the *slit\_id* is set to the slit sequence number in the left–right ordering of the spectra on the CCD: but in order to avoid confusion with tags assigned to identified slits, a negative integer is used in this case instead of a positive one.

**SLIT\_MAP\_MOS:** map of central wavelength on the CCD. This image is only created if the `--check` configuration parameter is set, and only in case the data are not long-slit. It has the same size of the `WAVELENGTH_MAP_MOS` image, from which it is derived. This product can be seen as an image of the mask cast on the CCD (see step 5 in Section 10, page 109): the slits images on the CCD are compared with

<sup>27</sup>The expected slit position on the CCD can even be very wrong, but pattern recognition algorithms would not be affected by that.

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	78 of 132

their positions on the mask, to derive the optical distortion model (see steps 6 and 7, always in Section 10).

Configuration parameters that may have some impact on this product are `--wdegree`, `--wmode`, `--wmosmode`, `--dispersion`, `--peakdetection`, `--wradius`, and `--wreject`.

**SPATIAL\_MAP\_MOS:** map of spatial positions on the CCD. This image is not produced for long-slit data. It has the same size of the CCD, where each pixel has the value of its distance (in CCD pixels) from the top edge of the spectrum it belongs to (see Figure 9.7.4). In case of confusion between nearby spectra, the spatial coordinate would just reflect the spatial curvature, and not the absolute spatial coordinate along the slit: see the note to the `CURV_TRACES_MOS` entry in this Section for more details.

Configuration parameters directly affecting this product are `--cdegree` and `--cmode`.

Configuration parameters having significant impact are `--startwavelength` and `--endwavelength`.

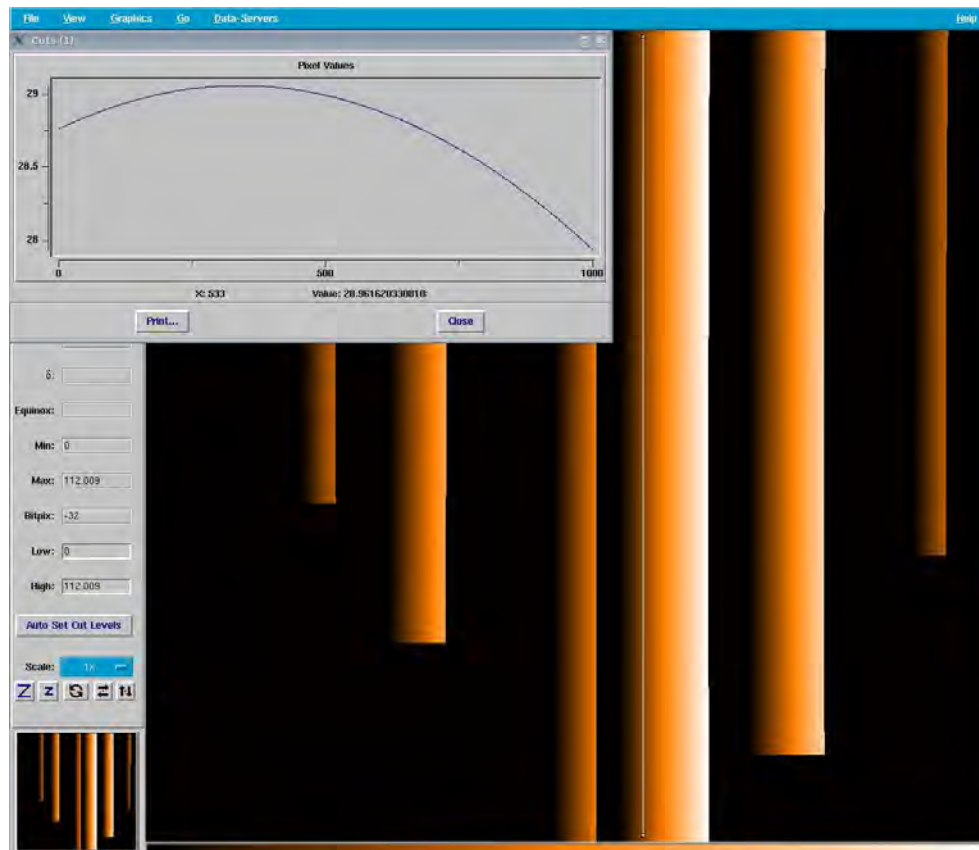


Figure 9.7.4: *SPATIAL\_MAP\_MOS* from a grism #11 flat field tracing, modeled with a 2nd degree polynomial. In the foreground is a plot of the distances from the rightmost spectral edge of all pixels from one CCD column.

**SPECTRA\_DETECTION\_MOS:** result of the preliminary wavelength calibration applied to the arc lamp exposure. This image is only created if the `--check` configuration parameter is set, and only in case the data are not long-slit.<sup>28</sup> The preliminary wavelength calibration is performed with the purpose of detecting and

<sup>28</sup> In case of long-slit data the preliminary wavelength calibration is actually identical to the final one.



ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	79 of 132

locating MOS spectra on the CCD (see step 2 in Section 10, page 109). In case of problems found in the recipe products, this image may be examined. All spectra should look aligned in wavelength, in particular around the central wavelength, that is the position used for constructing the slit map (SLIT\_MAP\_MOS). Gaps in the solution within a spectrum may appear, but if not overwhelming they have generally no consequences for the data reduction, because they are filled up consistently while creating the slit map. The  $x$  size of this image equals the  $x$  size of the REDUCED\_LAMP\_MOS image, while its  $y$  size matches the  $x$  size of the CCD (no spatial rectification performed).

Configuration parameters directly affecting this product are `--dispersion`, `--peakdetection`, and `--wdegree`. Configuration parameters having significant impact are `--startwavelength` and `--endwavelength`.

**SPECTRAL\_RESOLUTION\_MOS:** Mean spectral resolution for each reference arc lamp line. The table columns are the following:

**wavelength:** Wavelength of reference line.  
**fwhm:** Mean FWHM of reference line.  
**fwhm\_rms:** Standard deviation of all measured FWHM from all the CCD rows including the line.  
**resolution:** Mean spectral resolution, measured as the line *wavelength*, divided by its FWHM.  
**resolution\_rms:** Standard deviation of all the measured spectral resolutions from all the CCD rows including the line.

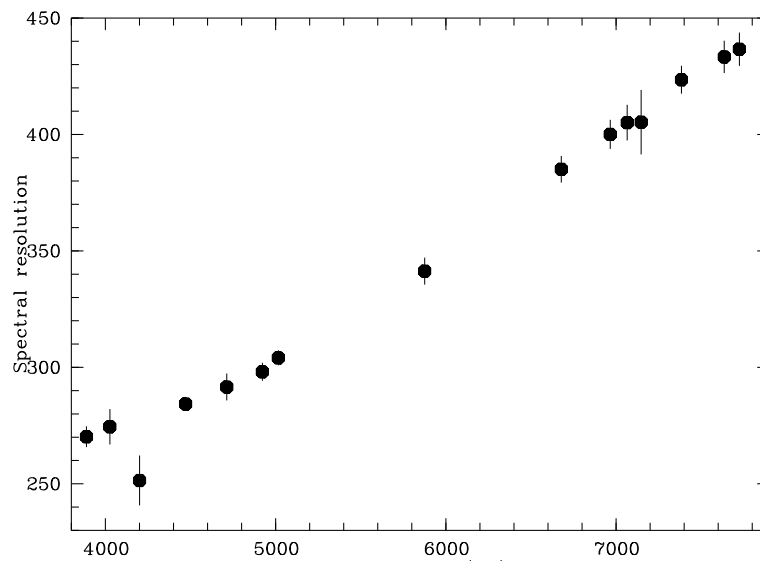


Figure 9.7.5: *Resolution vs. wavelength in a SPECTRAL\_RESOLUTION\_MOS table derived from a arc lamp exposure with grism #11.*

**WAVELENGTH\_MAP\_MOS:** map of wavelengths on the CCD. This image has the same size of the CCD, where each pixel has the value of the wavelength at its center, if available.

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--dispersion`, `--peakdetection`, `--wradius`, and `--wdegree`.

ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	80 of 132

### 9.7.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_calib* recipe will process the input data, and to some extent the product files that will be created. The parameters are conveniently divided into four main sections: wavelength calibration, spatial curvature calibration, flat field normalisation, and quality control.

#### Wavelength calibration

*--dispersion*: Expected spectral dispersion. *Default*: 0.0 Å/pixel

This parameter is mandatory (using the default 0.0 would generate an error message). This is a rough value of the expected spectral dispersion, used by the pattern-recognition algorithm described in Section 10.6.2, page 112. The dispersion values listed in the EFOSC2 User's Manual [10] are good, but in exceptional cases they might be tuned for recovering possible failures of the data reduction procedure, or to improve the quality of unsatisfactory results. In general, however, the spectral detection algorithm is very robust to modifications of this parameter: as a typical example, with a set of calibrations obtained with grism #13, for which the tabulated mean dispersion value is 2.77 Å/pixel, optimal results (at constant quality) were obtained within the interval 2.4–3.5 Å/pixel.<sup>29</sup>

Optimal values for this parameter, depending on the applied grism, are included in the GRISM\_TABLE (see Section 7.3, page 43). Note that the *--dispersion* value must refer to the real CCD pixel size: the given value of the dispersion is internally multiplied by the rebin factor, to match the real pixel size of the input data.<sup>30</sup> In this way the value of the parameter *--dispersion* is made independent from the CCD readout mode.

The value of the *--dispersion* parameter, multiplied by the rebin factor, is defining also the constant wavelength step at which the rectified arc lamp frame and other similar products are resampled (see the REDUCED\_LAMP\_MOS entry, page 75).

*--peakdetection*: Initial peak detection threshold. *Default*: 0.0 ADU

This parameter is mandatory (using the default 0.0 would generate an error message). This is a threshold value used in the preliminary peak detection task (see Section 10.6.1, page 110): the reference lines candidates are selected from peaks having a maximum value *above the background* higher than this threshold. Weaker entries of the input line catalog are recovered later on, after the preliminary wavelength calibration is obtained, if the parameter *--wradius* is set to a value greater than zero. It is however crucial that most of the reference lines are already detected at the earliest stage, if the pattern-recognition is meant to give the best possible results. A threshold value of 250 ADU is suitable in most cases, but sometimes the recovery of fainter reference lines may require to lower the threshold almost down to noise level.<sup>31</sup> Optimal values for this parameter, depending on the applied grism, are included in the GRISM\_TABLE (see Section 7.3, page 43).

*--startwavelength*: Start wavelength in spectral extraction. *Default*: 0.0 Ångstrom

See the *--endwavelength* parameter

<sup>29</sup>This is not a guarantee for all kinds of data: this tolerance mostly depends on the dispersion law of the applied grism, and on the available arc lamp lines.

<sup>30</sup>The rebin factor along the dispersion direction is written to the FITS header keyword ESO DET WIN1 BINX.

<sup>31</sup>Lowering this threshold below a 3- $\sigma$  noise level would completely destroy the observed pattern. In such extreme cases a preliminary smoothing of the input arc lamp exposure for reducing the random noise may help.



<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	81 of 132

*--endwavelength*: End wavelength in spectral extraction. *Default*: 0.0 Ångstrom

This parameter, together with the *--startwavelength* parameter, defines the wavelength interval where calibration is attempted: this interval may not be entirely contained in the CCD for all spectra. Default values of the extraction interval, depending on the applied grism, are included in the GRISM\_TABLE (see Section 7.3, page 43). If both *--startwavelength* and *--endwavelength* are left to 0.0, the extraction interval is computed automatically as the interval between the first and the last identified arc lamp reference lines, extrapolated by 10% at its blue and red ends (see Section 10.6.3, page 115).

*--wdegree*: Degree of wavelength calibration polynomial. *Default*: 0

This parameter is mandatory (using the default 0 would generate an error message). The degree used for the wavelength calibration polynomial should be the lowest which would provide non-systematic residuals to the solution (see the DISP\_RESIDU ALS\_MOS entry, page 73).

Note that the *--wdegree* parameter should be more correctly intended as the *maximum* applicable polynomial order: the polynomial is really adapted to the number of identified arc lamp lines used in the fit. This is necessary, because spectra from slits with very high offsets on the telescope focal plane may not be entirely contained in the CCD, and several arc lamp reference lines might be unavailable for calibration. Such spectra would not be properly calibrated if a polynomial with too many free parameters were used. As a rule, a polynomial with the specified *--wdegree* is only used if the number of identified lines is at least twice the number of free parameters: if this were not the case, the applied polynomial order would be

$$n = \text{floor}\left(\frac{N}{2}\right) - 1$$

where  $N$  is the number of identified reference lines. Accordingly, no solution is computed if less than 4 reference lines are identified.

*--wradius*: Search radius, if iterating pattern-matching with first-guess method. *Default*: 4 pixel

If this parameter is greater than zero, the peak identification is iterated using the pattern-matching solution as a first-guess model: the wavelengths listed in the input line catalog are transformed to CCD pixel positions using this model, and a peak is searched within the specified search radius.<sup>32</sup> Alternatively, setting *--wradius* = 0 means to accept the pattern-matching solution without further processing. Iterating the solution makes the wavelength calibration more robust, and increasing the search radius may help sometimes to recover from a bad result. It may happen however that the pattern-matching solution is more accurate than the one based on the iteration: this is because in the pattern-matching task peaks are identified by their being part of a pattern, while with a first-guess model each peak is identified by its vicinity to its expected position: the latter approach may lead to occasional misidentifications, and may be more negatively affected by contamination and lines blending (see also Section 10.6.1, page 110).

*--wreject*: Rejection threshold in dispersion relation fit (pixel). *Default*: 0.7 pixel

The wavelength calibration polynomial fit is iterated excluding any reference line position displaying a residual greater than the specified threshold.

<sup>32</sup> If a search radius greater than zero is specified, but the reference lines widths are even greater, the search radius is automatically set to the actual lines widths.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	82 of 132

*--wmode*: Interpolation mode of wavelength solution (0 = no interpolation, 1 = fill gaps, 2 = global model).  
*Default*: 2

This parameter only affects the processing of long-slit data. Given the wide availability of similar information on a long slit spectrum, it is conceivable an improvement of the quality of the wavelength calibration by modeling the global trend of the local solutions obtained from each CCD row. If *--wmode* = 1 the global model is applied just to fill possible gaps in the solution, maintaining the result of the local calibrations where they are available. If *--wmode* = 2 the global model solution is used for replacing also the available local solutions. No interpolation is applied to the data if *--wmode* = 0.

*--wmosmode*: Interpolation mode of wavelength solution (0 = no interpolation, 1 = local (slit) solution, 2 = global model). *Default*: 0

This parameter only affects the processing of generic MOS data. It is conceivable an improvement of the quality of the wavelength calibration by modeling the trend of the solutions within each slit, or even globally (as a function of the position of the slits on the focal plane). If *--wmosmode* = 1 the solutions within each slit are replaced by their best linear fit, while if *--wmosmode* = 2 a bivariate, second order global solution is fitted to the available local solutions and then replaces them. No interpolation is applied to the data if *--wmosmode* = 0, and this is the default.

*--wcolumn*: Name of line catalog table column with wavelengths. *Default*: WLEN

This is the name of the `LINE_CATALOG` table column where the arc lamp reference wavelengths are listed. The default is the name of the relevant column in the standard line catalog (see also the `LINE_CATALOG` entry on page 71). This would allow the usage of any FITS table, supplied by the user, containing a list of wavelengths to be processed by the pattern-recognition task. The only requirement is that the listed wavelengths are given in Ångström, and that they are sorted from blue to red.

## Spatial curvature calibration

*--cdegree*: Degree of spatial curvature polynomial. *Default*: 0

This parameter is mandatory (using the default 0 would generate an error message). In general a 2nd degree polynomial gives good results. Optimal values depending on the applied grism are included in the `GRISM_TABLE` (see Section 7.3, page 43).

Systematic residuals, oscillating from positive to negative offsets of about 0.1–0.2 pixels, are frequently observed, and are confirmed also by other data reduction systems (see Figure 9.7.6). The systematic residuals are due to the changing pixelisation of the spectral edges on the CCD, and therefore they should not be considered physical. A low degree polynomial fit appropriately circumvents this effect by cutting through such oscillations. Trying to fit such residuals with higher degree polynomials would lead to unstable and unrealistic solutions.

*--cmode*: Interpolation mode of curvature solution (0 = no interpolation, 1 = fill gaps, 2 = global model).  
*Default*: 1

This parameter does not affect the processing of long-slit data. Using a global description of the spatial curvature helps to extract also those spectra whose edges cannot be traced because of confusion with nearby spectra. If *--cmode* = 0 the only recovery strategy consists in supplying a missing trace by replicating the trace of the opposite edge (opportunely shifted). This is however not very accurate, and it is

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	83 of 132

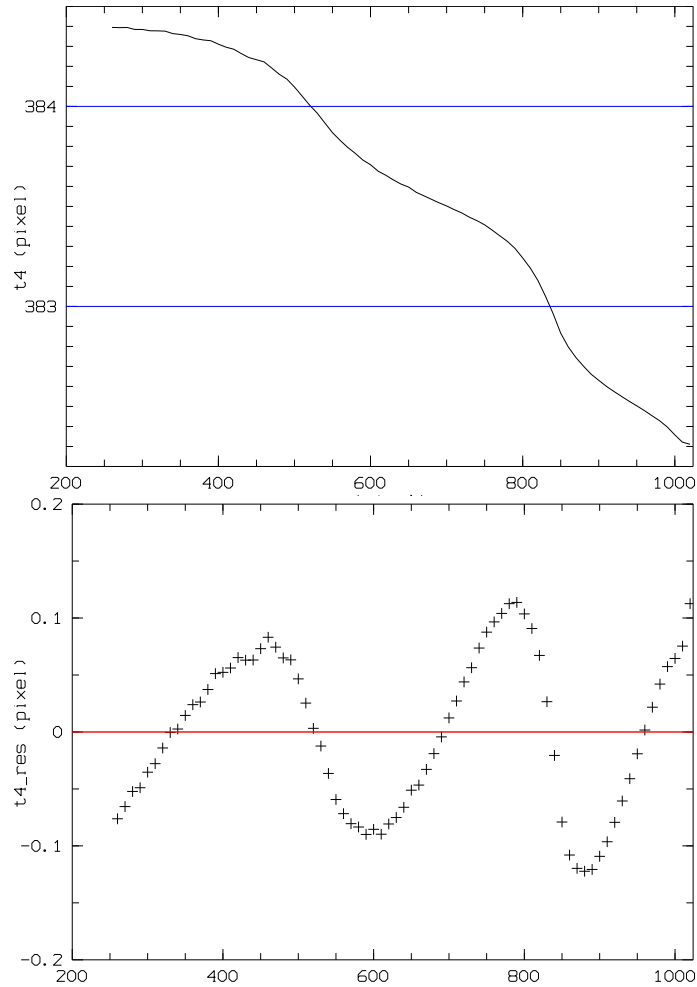


Figure 9.7.6: *Systematic residuals of curvature model (from a grism #3 flat field exposure).*

not even applicable if a tracing is missing for both edges of a slit spectrum.<sup>33</sup> By setting `--cmode = 1` a global trend of the curvature coefficients would be determined, allowing to derive a curvature model also for the spectral edges that are lacking a direct tracing. Setting `--cmode = 2` would recompute the curvature model also for the spectra where a local solution is available: this is generally not advisable, because a local solution is generally more accurate than the one derivable from the global solution.

`--slit_ident`: Attempt slit identification. *Default*: TRUE

This parameter does not affect the processing of long-slit data. Setting this parameter activates the 2D pattern-recognition task linking the slits positions on the mask with those on the CCD (see Section 10.6.6, page 116). In principle, the only outcome would be the identification of the detected spectra, i.e., their association to the slits on the mask, that is not required for a complete processing of the data: spectra would be extracted anyway, even if lacking a proper identification.<sup>34</sup> However, as shown in Section 10.6.6,

<sup>33</sup>In this case the spectrum would not be extracted.

<sup>34</sup>In fact, the 2D pattern-recognition task would fail in case less than three spectra were detected on the CCD, and also in case the

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	84 of 132

the 2D pattern-recognition is also used to define an optical distortion model which helps to improve the accuracy of the preliminary spectra detection, and in some case even to allow the recovery of spectra that were lost to the spectral identification task. This is why the slit identification should always be requested: the only reason why the parameter `--slit_ident` was defined is to offer to possibility to switch the 2D pattern-matching task off in case this affected negatively the data reduction process.<sup>35</sup> Note also that excluding the slit identification would also allow to reduce data from instruments different from EFOSC2.<sup>36</sup>

## Flat field normalisation

`--stack_method`: Frames combination method (**average** = simple average of all input frames, **median** = median stacking of all input frames, **minmax** = stacking frames with minmax rejection, **ksigma** = average frames with k-sigma clipping). *Default: average*

This parameter affects the way the raw flat field frames are stacked to produce the master flat field frame which will then be normalised.

`--minrejection`: Number of lowest values to be rejected. [1]

`--maxrejection`: Number of highest values to be rejected. [1]

These parameters are only active if `--stack_method=minmax`. See more details in the description given in Section 9.1.3, page 52.

`--klow`: Low threshold in ksigma method. [3.0]

`--khigh`: High threshold in ksigma method. [3.0]

`--kiter`: Max number of iterations in ksigma method. [999]

These parameters are only active if `--stack_method=ksigma`. See more details in the description given in Section 9.1.3, page 52.

`--sdegree`: Degree of flat field fitting polynomial along spatial direction. *Default: 4*

This parameter only affects the processing of long-slit data. If the configuration parameter `--sdegree` is set to a non-negative value, the master flat field normalisation is performed by modeling its large scale trend with a polynomial fitted along the spatial direction (and not along the dispersion direction, as for the case of shorter slits), for each CCD column. If `--sdegree < 0` the illumination trend is obtained instead by median filtering with a runningbox of sizes `--dradius` and `--sradius`.

`--ddegree`: Degree of flat field fitting polynomial along dispersion direction. *Default: -1*

This parameter does not affect the processing of long-slit data. If `--ddegree` is set to a non-negative value, the master flat field normalisation is performed by modeling its large scale trend with a polynomial fitted

spectra were regularly spaced, as it happens with some calibration masks: but in neither situation spectra identification represents a practical issue.

<sup>35</sup>This was never seen to happen, but one never knows...

<sup>36</sup>The only reason why the self-calibrating recipes described here are not readily usable for any MOS instrument is that the way the slit characteristics are listed in the data FITS headers is not standardised. It should also be pointed out that these recipes are not designed to handle data with spectral multiplexing, as those from low-resolution observations made with VIMOS.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	85 of 132

along the dispersion direction. The flat field spectra are spatially rectified applying the curvature model before the fit is performed, and the smoothed result is mapped back to the CCD frame before being used for normalising the master flat field. If `--ddegree < 0` the illumination trend is obtained instead by median filtering the spatially rectified spectra with a running box of sizes `--dradius` and `--sradius`. Polynomial modeling should be preferred whenever appropriate, i.e., in all those cases where the flat field illumination does not vary with the wavelength in a too complex way, and the fit residuals would not display systematic displacements from the flat field illumination trend.

`--dradius`: Smooth box radius for flat field along dispersion direction. *Default*: 10 pixel

See the `--sradius` parameter

`--sradius`: Smooth box radius for flat field along spatial direction. *Default*: 10 pixel

This parameter, together with `--dradius`, affects the processing of long-slit data only in case `--sdegree` is negative, and the processing of multi-spectra data only in case `--ddegree` is negative. `--sradius` and `--dradius` are the sizes (in pixel) along the spatial and dispersion directions of the runningbox applied for smoothing the master flat field before its final normalisation.

## Quality control

`--qc`: Compute QC1 parameters. *Default*: TRUE

Setting this parameter will trigger the Quality Control parameters computation. This is just relevant for the on-line pipeline run automatically on La Silla. See Section 9.7.4 for a list of the computed parameters.

`--check`: Create intermediate products. *Default*: FALSE

Setting this parameter will write to disk some intermediate products of the data reduction procedure. This may be useful for debug purposes, in case of unsatisfactory results or failures of the `efosc_calib` recipe. Currently the created intermediate products are SPECTRA\_DETECTION\_MOS and SLIT\_MAP\_MOS (see page 77).

### 9.7.4 Quality control parameters

Currently the following QC parameters, used by PSO, are evaluated by the `efosc_calib` recipe.

**QC WAVE ACCURACY**: Mean wavelength calibration accuracy. *Units*: pixel

This is the mean value of the **error** column in table DISP\_COEFF\_MOS (see the corresponding entry in this Section 9.7.2, page 71).

**QC WAVE ACCURACY ERROR**: Error of mean wavelength calibration accuracy. *Units*: pixel

This is the standard deviation of the **error** column in table DISP\_COEFF\_MOS (see the corresponding entry in this Section 9.7.2, page 71).

**QC TRACE MAX CURVATURE**: Max curvature in spectral tracing. *units*: (Y pixel/X pixel<sup>2</sup>)

This is computed as the max absolute value of the column "c2" of the CURV\_COEFF\_MOS table.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	86 of 132

**QC TRACE MAX SLOPE:** Max slope in spectral tracing (Y pixel/X pixel)

This is computed as the max absolute value of the column "c1" of the CURV\_COEFF\_MOS table.

**QC MOS RESOLUTION:** Mean spectral resolution of all identified arc lamp lines. *Units: none*

From a wavelength calibrated arc lamp exposure, the mean spectral resolution for each line in catalog is evaluated as the ratio between its wavelength and its FWHM. The results are written to the SPECTRAL\_RESOLUTION\_MOS table (see page 79), and the mean resolution of all lines is written to the keyword QC MOS RESOLUTION of its FITS header.

**QC MOS RESOLUTION RMS:** Scatter of all computed spectral resolutions. *Units: none*

Population RMS of all values contributing to the QC MOS RESOLUTION. This value is written to the keyword QC MOS RESOLUTION RMS of the SPECTRAL\_RESOLUTION\_MOS table (see above).

**QC MOS RESOLUTION NLINES:** Number of lines used for computing the mean resolution. *Units: none*

Number of reference arc lamp lines used in the computation of the mean resolution. This value is written to the keyword QC MOS RESOLUTION NLINES of the SPECTRAL\_RESOLUTION\_MOS table (see above).

**QC MOS RESOLUTION NWAVE:** Number of wavelengths used for computing the mean resolution. *Units: none*

Number of distinct arc lamp lines wavelengths used in the computation of the mean resolution. This value is written to the keyword QC MOS RESOLUTION NWAVE of the SPECTRAL\_RESOLUTION\_MOS table (see above).

**QC MOS RESOLUTION MEANRMS:** Mean RMS of spectral resolution at each wavelength. *Units: none*

Mean RMS of in the determination of the spectral resolution at each wavelength.

**QC MOS CENTRAL WAVELENGTH:** Wavelength at CCD center. *Units: Ångstrom*

After the wavelength calibration is obtained from a long-slit arc lamp exposure, the wavelength corresponding to the central CCD pixel is calculated. This parameter is not computed for generic MOS observations, but just for long-slit observations. The central wavelength is written to the keyword QC MOS CENTRAL WAVELENGTH of the wavelength map FITS header (see entry WAVELENGTH\_MAP\_MOS, page 79).

## 9.8 efosc\_science

This recipe is used for reducing EFOSC2 scientific spectra applying the extraction mask and the normalised flat field created by the recipe *efosc\_calib*. In case of a standard star observation, efficiency and response curves are also calculated.

The slit spectra are bias subtracted, flat fielded if requested, and remapped eliminating the optical distortions. The input wavelength calibration can optionally be adjusted to a number of reference sky lines. Finally, objects are searched and extracted from all the slit spectra.

In the following sections the word SCIENCE may be alternatively read STANDARD, as the spectroscopic standard stars exposures are reduced as scientific exposures. In case of standard star observations the SCI acronym in the products names should also be read STD.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	87 of 132

### 9.8.1 Input files

In alphabetical order:

**CURV\_COEFF\_MOS:** *required* table with spatial curvature coefficients, however *not required* for long-slit observations.<sup>37</sup> This table is produced by the *efosc\_calib* recipe (see page 71).

**DISP\_COEFF\_MOS:** *required* table with wavelength solution coefficients. This table is produced by the *efosc\_calib* recipe (see page 72).

**EXTINCT\_TABLE:** *optional* atmospheric extinction table. If a standard star exposure is specified in input, and efficiency and response curves are wanted, this table must also be specified in input. It must also be specified in case a spectro-photometric calibration should be applied to the extracted spectra (i.e., when the parameter *--photometry* is set to "true"). See Section 7.6, page 45.

**GRISM\_TABLE:** *optional* grism table. See Section 7.3, page 43.

**MASTER\_BIAS:** *required* master bias frame. Just one should be given.

**MASTER\_NORM\_FLAT\_MOS:** *optional* normalised flat field. This frame is produced by the *efosc\_calib* recipe (see page 75), and it must be provided only if the flat field correction is requested (see configuration parameter *--flatfield*, Section 9.8.3, page 93).

**SKY\_LINE\_CATALOG:** *optional* sky lines catalog. It must contain the reference wavelengths (in Ångstrom) of the sky lines used for adjusting the input wavelength solution to the observed scientific spectra. The only requirement for this table is to contain a column listing such wavelengths, whose name should be specified using the configuration parameter *--wcolumn* (see Section 9.8.3, page 93). If the alignment of the wavelength solution to the sky lines is requested, and a **SKY\_LINE\_CATALOG** is not specified in input, an internal sky line catalog is used instead (see Table 9.8.1).

**SCIENCE\_MOS:** *required* scientific exposure. Just one frame should be specified.

**SLIT\_LOCATION\_MOS:** *required* table of slits positions, however *not required* for long-slit observations. This table is produced by the *efosc\_calib* recipe. (See page 77).

**SPECPHOT\_TABLE:** *optional* table with efficiency and response curves. It must be specified in case a spectro-photometric calibration should be applied to the extracted spectra (i.e., when the parameter *--photometry* is set to "true"). This table is also a product of this recipe, and it is described in more detail in the next Section. See also Section 10.5, page 109, about how the photometric calibration is applied.

**STD\_FLUX\_TABLE:** *optional* standard star flux table. If a standard star exposure is specified in input, and efficiency and response curves are wanted, this table must also be specified in input. Its keyword **ESO OBS TARG NAME** must match the one in the input standard star exposure frame. See Section 7.7, page 45.

<sup>37</sup> Currently no spatial curvature correction is applied to long-slit data, this will be fixed in one of the next releases.



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	88 of 132

Wavelength	Low resolution	Wavelength	Low resolution
5577.338	✓	7329.148	
5889.953		7340.885	
5895.923		7358.659	
5915.301		7571.746	✓
5932.862		7750.640	
5953.420		7759.996	
6257.961		7794.112	
6287.434		7808.467	
6300.304	✓	7821.503	
6306.869		7841.266	
6363.780		7913.708	
6498.729		7949.204	
6533.044		7964.650	✓
6553.617		7993.332	✓
6841.945		8014.059	
6863.955	✓	8310.719	
6870.994		8344.602	
6889.288		8382.392	
6900.833		8399.170	
6912.623		8415.231	
6923.220		8430.174	
6939.521		8452.250	
6969.930		8493.389	
7003.858		8791.186	
7244.907		8827.096	
7276.405		8885.850	
7284.439		8903.114	
7316.282		8943.395	
		8988.366	

Table 9.8.1: *Default sky lines wavelengths used by the recipe efosc\_science. The marked lines are those used on data from low resolution grisms, i.e., all grisms with 300 gr/mm or less.*



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	89 of 132

## 9.8.2 Output files

Not all output frames listed here are always produced. Some of them are created only on request, and some other are never created in case of long-slit data. Here is the list of all the possible output frames, in alphabetical order, together with a list of related configuration parameters:<sup>38</sup>

**DISP\_COEFF\_SCI\_MOS:** This adjustment of the input `DISP_COEFF_MOS` table is only created in case the alignment of the wavelength solution to the sky lines is requested (see the configuration parameter `--skyalign`, Section 9.8.3, page 93). For a description of this product see the `DISP_COEFF_MOS` entry on page 72. In the `DISP_COEFF_SCI_MOS` table the *error* column content is computed by (quadratically) summing the errors of the input wavelength solution with the errors of the sky alignment fit. Similarly, in the *nlines* column the number of sky lines used for the alignment replaces the number of reference arc lamp lines on which the input calibration was based.

Configuration parameters directly affecting this product are `--skyalign`, `--startwavelength` and `--endwavelength`.

**GLOBAL\_SKY\_SPECTRUM\_MOS:** table with supersampled sky spectrum, created only if the global sky subtraction is requested (see configuration parameter `--skyglobal`, Section 9.8.3, page 93). Each wavelength bin is half the resampling step, multiplied by the CCD readout rebin factor (see the configuration parameter `--dispersion`, Section 9.8.3, page 93).

The spectra contained in the input scientific exposure (see the `SCIENCE_MOS` entry on page 87) are assumed to contain altogether at least 50% of their pixels on the sky. Moreover, all the *scientific* slits are assumed to have the same width.<sup>39</sup> The wavelength map derived from the input `DISP_COEFF_MOS` table (possibly adjusted by the sky lines alignment task) is used to map all the spectral signal in the CCD into a grid of wavelength bins. The sky spectrum is computed as the median level of all the pixel values of all the CCD spectra in each wavelength bin. The median of the contributing wavelengths (which are not uniformly distributed within the bin) is also assigned to each bin. Empty bins are computed by linear interpolation between the nearest valid bins, and in this case a bin is assigned its central wavelength.

The global sky table includes the following columns:

**wavelength:** Bin wavelength.  
**sky:** Median signal level for each bin.  
**npoints:** Number of points contributing to each bin.

Configuration parameters directly affecting this product are `--skyglobal`, `--time_normalise`, `--startwavelength` and `--endwavelength`.

**MAPPED\_FLUX\_SCI\_MOS:** photometrically calibrated scientific slit spectra. This image matches the image `MAPPED_SCI_MOS`, and is produced only if the spectrophotometric calibration was requested.

Configuration parameters having significant impact are `--photometry`.

<sup>38</sup>See Section 9.8.3, page 93, for a complete description of the recipe configuration parameters.

<sup>39</sup>If this were not the case, the global sky model quality would be poorer, and only the slits with a median slit width would be properly corrected. This may be fixed by applying a local sky subtraction following the global one, but this would eliminate the advantages of using a global sky model.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	90 of 132

**MAPPED\_ALL\_SCI\_MOS:** image with rectified and wavelength calibrated slit spectra. Its  $x$  size depends on the spectral extraction range ( $\lambda_{min}, \lambda_{max}$ ) and on the specified resampling step in wavelength units per pixel,  $D$ , defined by the configuration parameter `--dispersion` (see Section 9.8.3, page 93):

$$N_x = floor\left(\frac{\lambda_{max} - \lambda_{min}}{D}\right)$$

The  $y$  size is determined in the same way as for the REDUCED\_LAMP\_MOS frame (see page 75).

Note that resampling the original spectrum at a constant wavelength step introduces distortions of the signal, which depend on the original signal pixelisation on the CCD, and it introduces noise correlation. See the final note to the REDUCED\_LAMP\_MOS entry on page 75.

Configuration parameters directly affecting this product are `--dispersion`, `--flux`, `--flatfield`, `--time_normalise`, `--skyalign`, `--startwavelength` and `--endwavelength`.

**MAPPED\_SCI\_MOS:** image with rectified, wavelength calibrated and sky subtracted slit spectra. This image matches in size the MAPPED\_ALL\_SCI\_MOS image, and is produced only if any kind of sky subtraction is requested.

Configuration parameters directly affecting this product are `--dispersion`, `--flux`, `--cosmics`, `--flatfield`, `--time_normalise`, `--skyalign`, `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--skymedian`, `--skylocal`, and `--skyglobal`.

**MAPPED\_SKY\_SCI\_MOS:** image with rectified and wavelength calibrated slit sky spectra. This image contains the modeled sky which was subtracted from the scientific data, either before or after the scientific spectra rectification (or even both, if the configuration parameters `--skyglobal` and `--skymedian` were both set: the contribution of the global sky model is included in this image even if the global sky subtraction is really applied to the data before their rectification). The sky model component subtracted before the rectification of the scientific spectra can be viewed separately in the GLOBAL\_SKY\_SPECTRUM\_MOS and the UNMAPPED\_SKY\_SCI\_MOS products.

The MAPPED\_SKY\_SCI\_MOS also includes the identified cosmic ray signal in case the cosmic rays removal is requested (see configuration parameter `--cosmics`, Section 9.8.3, page 93).

Configuration parameters directly affecting this product are `--skymedian`, `--skyglobal`, `--skylocal`, `--cosmics`, `--time_normalise`, `--startwavelength` and `--endwavelength`.

Configuration parameters having significant impact are `--skyalign`, `--flux`, and `--flatfield`.

**OBJECT\_TABLE\_SCI\_MOS:** This table is an expansion of the input SLIT\_LOCATION\_MOS table (see page 77), where the positions and the extraction spatial intervals of the detected objects are also included. This table is produced only if any kind of sky subtraction is requested, otherwise no object detection or extraction is attempted. The object table columns are the following:

<b>slit_id:</b>	Slit identification number
<b>xtop:</b>	$x$ CCD position of central wavelength from left end of slit.
<b>ytop:</b>	$y$ CCD position of central wavelength from left end of slit.
<b>xbottom:</b>	$x$ CCD position of central wavelength from right end of slit.
<b>ybottom:</b>	$y$ CCD position of central wavelength from right end of slit.
<b>position:</b>	First row of the rectified images (MAPPED_ALL_SCI_MOS)

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	91 of 132

and MAPPED\_SCI\_MOS) containing the rectified slit spectrum. Image rows are counted from bottom, starting from 0.

**length:** Number of rows in rectified images including the slit spectrum.

**object\_1, object\_2, ...:** Detected objects positions in the rectified images.

**start\_1, start\_2, ...:** Start position of the extraction interval for each object.

**end\_1, end\_2, ...:** End position of the extraction interval for each object.

**row\_1, row\_2, ...:** Row number of the REDUCED\_SCI\_MOS image containing the extracted object spectrum. Image rows are counted from bottom, starting from 0.

Configuration parameters directly affecting this product are *--slit\_margin*, *--ext\_radius*, *--cont\_radius*.

Configuration parameters that may have significant impact are *--startwavelength* and *--endwavelength*.

**REDUCED\_ERROR\_SCI\_MOS:** image with errors (one sigma level) corresponding to the extracted objects spectra. This image matches the REDUCED\_SCI\_MOS image.

Configuration parameters directly affecting this product are *--dispersion*, *--ext\_mode*, *--time\_normalise*, *--startwavelength* and *--endwavelength*.

Configuration parameters having significant impact are *--slit\_margin*, *--ext\_radius*, *--cont\_radius*, and *--flux*.

**REDUCED\_FLUX\_ERROR\_SCI\_MOS:** error on photometrically calibrated scientific spectra. This image matches the REDUCED\_ERROR\_SCI\_MOS image, and it is produced only if the spectrophotometric calibration was requested.

Configuration parameters having significant impact are *--photometry*.

**REDUCED\_FLUX\_SCI\_MOS:** photometrically calibrated scientific spectra. This image matches the REDUCED\_SCI\_MOS image, and it is produced only if the spectrophotometric calibration was requested.

Configuration parameters having significant impact are *--photometry*.

**REDUCED\_SCI\_MOS:** image with extracted objects spectra. This image has the same *x* size of the image with the extracted slit spectra, MAPPED\_SCI\_MOS, and as many rows as the detected and extracted object spectra. Extracted spectra are written to the image rows listed in the OBJECT\_TABLE\_SCI\_MOS table.

Configuration parameters directly affecting this product are *--dispersion*, *--ext\_mode*, *--time\_normalise*, *--startwavelength* and *--endwavelength*.

Configuration parameters having significant impact are *--slit\_margin*, *--ext\_radius*, *--cont\_radius*, *--skyalign*, *--flux*, *--flatfield*, *--skyglobal*, *--skylocal*, *--skymedian*, and *--cosmics*.

**REDUCED\_SKY\_SCI\_MOS:** image with sky corresponding to the extracted objects spectra. The sky is extracted in the same way as the objects, e.g., if optimal weights were applied to the object extraction, the same weights are applied to the sky extraction. This image matches the REDUCED\_SCI\_MOS image.

Configuration parameters directly affecting this product are *--dispersion*, *--ext\_mode*, *--time\_normalise*, *--startwavelength* and *--endwavelength*.

Configuration parameters having significant impact are *--slit\_margin*, *--ext\_radius*, *--cont\_radius*, *--skyalign*, *--flux*, *--flatfield*, *--skylocal*, *--skyglobal* and *--skymedian*.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	92 of 132

**SKY\_SHIFTS\_LONG\_SCI\_MOS:** table containing the observed sky lines offsets that were used for adjusting the input wavelength solution. This table is only produced if the sky lines alignment is requested (see configuration parameter `--skyalign`, Section 9.8.3, page 93), and is specific to long-slit data (for multi-spectra observations the `SKY_SHIFTS_SLIT_SCI_MOS` table is produced instead).

This table has as many rows as the `MAPPED_ALL_SCI_MOS` image, and it contains two columns for each of the examined sky lines:

**off\_5577:** Observed skyline offset (in pixel) at each CCD row. The integer truncation of each sky line wavelength is used for composing the corresponding column name (in this example the column name refers to the 5577.338 O I emission).  
**fit\_5577:** Modeling of the *off\_5577* offsets.

This table may be very useful for judging what would be the most appropriate modeling of the observed offsets, and to what extent the input wavelength calibration really needs to be adjusted.

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

**SKY\_SHIFTS\_SLIT\_SCI\_MOS:** table containing the observed sky lines offsets that were used for adjusting the input wavelength solution. This table is only produced if the sky lines alignment is requested (see configuration parameter `--skyalign`, Section 9.8.3, page 93), and is specific to multi-spectra observations (for long-slit observations the `SKY_SHIFTS_LONG_SCI_MOS` table is produced instead). This table has one row for each of the sky lines used for the alignment, and one column for each slit where sky lines could be detected.

The included columns are the following:

**wave:** Sky line wavelength.  
**offset<slit\_id>:** Observed offsets for the slit spectrum with identification *slit\_id*.

This table may be very useful for judging what would be the most appropriate modeling of the observed offsets, and to what extent the input wavelength calibration really needs to be adjusted.

Configuration parameters directly affecting this product are `--startwavelength` and `--endwavelength`.

**SPECPHOT\_TABLE:** table with efficiency and response curves, produced only when input includes a standard star observation, an `EXTINCT_TABLE`, and the appropriate `STD_FLUX_TABLE` matching the observed star.

The `SPECPHOT_TABLE` include the following columns:

**wave:** Wavelength ( $\text{\AA}$ )  
**std\_flux:** Standard star flux ( $10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ )  
**obs\_flux:** Observed flux ( $e^- \text{ s}^{-1} \text{ \AA}^{-1}$ )  
**raw\_efficiency:** Ratio between input and detected photons  
**efficiency:** Heavily smoothed version of **raw\_efficiency**  
**raw\_response:** Ratio between **std\_flux** and **obs\_flux**  
**response:** Heavily smoothed version of **raw\_response**

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	93 of 132

The way this table is produced is described in Section 10.4, page 108.

Configuration parameters directly affecting this product are *--response*, *--startwavelength*, *--endwavelength*, and *--flux*.

**UNMAPPED\_SCI\_MOS:** image with the sky subtracted scientific spectra on the CCD frame, created only if the global or the local sky subtraction is requested (see the configuration parameters *--skyglobal* and *--skylocal*, Section 9.8.3, page 93).<sup>40</sup> This image is derived subtracting the UNMAPPED\_SKY\_SCI\_MOS from the bias subtracted and flat fielded scientific frame.

Configuration parameters directly affecting this product are *--skyglobal*, *--skylocal*, *--skyalign*, *--time\_normalise*, *--startwavelength* and *--endwavelength*.

**UNMAPPED\_SKY\_SCI\_MOS:** this image has the same size of the CCD, and is created if either the global or the local sky subtraction is requested.

If *--skyglobal* is set (see the configuration parameter *--skyglobal*, Section 9.8.3, page 93), this image contains the global sky model mapped on the CCD frame, derived from the supersampled sky spectrum contained in the GLOBAL\_SKY\_SPECTRUM\_MOS table. Each one of its pixels is assigned a value obtained by linear interpolation of the two wavelengths of the supersampled spectrum that are closest to its wavelength.

If *--skylocal* is set (see the configuration parameter *--skylocal*, Section 9.8.3, page 93), this image contains the sky model obtained by interpolating the sky signal trend along the spatial direction, directly on the CCD frame.

The global sky subtraction consists of subtracting this image from the original bias subtracted and flat field corrected scientific exposure.

Configuration parameters directly affecting this product are *--skyglobal*, *--skyalign*, *--time\_normalise*, *--startwavelength* and *--endwavelength*.

**WAVELENGTH\_MAP\_SCI\_MOS:** This upgraded version of the wavelength map is only produced in case the adjustment of the wavelength solution to the sky lines is requested (see the configuration parameter *--skyalign*, Section 9.8.3, page 93). For a description of this product see the WAVELENGTH\_MAP\_MOS entry on page 79. Note that the coordinate system of the WAVELENGTH\_MAP frames will generally differ, because they are derived from different input data: the coordinate system of WAVELENGTH\_MAP\_MOS is inherited from the arc lamp frame header, while the coordinate system of WAVELENGTH\_MAP\_SCI\_MOS is inherited from the scientific frame header.

Configuration parameters directly affecting this product are *--skyalign*, *--startwavelength* and *--endwavelength*.

### 9.8.3 Configuration parameters

The configuration parameters setting determines the way the *efosc\_science* recipe will process the input data, and to some extent the product files that will be created. The parameters are conveniently divided into six main sections: wavelength calibration, spatial curvature calibration, flat field correction, sky subtraction, objects detection and extraction, and flux calibration.

<sup>40</sup> In the case of long-slit data this image is only created with the *--skyglobal* option, because the *--skylocal* option is not available.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	94 of 132

## Wavelength calibration

`--skyalign`: Polynomial order for sky lines alignment. *Default*: 0

The input wavelength calibration can be adjusted to the observed positions of a set of sky lines, whose wavelengths are listed in an input catalog. The observed sky lines offsets from their expected positions (see entries `SKY_SHIFTS_LONG_SCI_MOS` and `SKY_SHIFTS_SLIT_SCI_MOS`, page 92) are fitted by polynomials that are then added to the input wavelength calibration polynomials (see `DISP_COEFF_MOS` entry on page 72). A `--skyalign = 0` would just determine a median offset from all the observed sky lines, while `--skyalign = 1` would try to fit a slope (rarely useful, but sometimes sky lines offsets display a significant dependency on the wavelength, due to a variation of the mean spectral dispersion with respect to the day calibrations). Polynomials with order greater than 2 generate a friendly error message. Setting `--skyalign < 0` disables any sky line alignment, accepting the input wavelength calibration as-is.

Note that the `--skyalign` parameter should be more correctly intended as the *maximum* applicable polynomial order: the polynomial is really adapted to the number of identified sky lines used in the fit. As a rule, a polynomial with the specified order is only used if the number of identified sky lines is at least greater than the number of free parameters: if this were not the case, the applied polynomial order would be

$$n = N - 1$$

where  $N$  is the number of identified sky lines. Consistently, for  $n = 0$  a median offset would be computed.

`--wcolumn`: Name of sky line catalog table column with wavelengths. *Default*: `WLEN`

This is the name of the `SKY_LINE_CATALOG` table column where the arc lamp reference wavelengths are listed. This would allow the usage of any FITS table, supplied by the user, containing a list of sky lines wavelengths to be used by the sky lines alignment task. The only requirement is that the listed wavelengths are given in Ångstrom, and that they are sorted from blue to red. Note that it is not necessary to provide a sky lines catalog to make the sky alignment work: see entry `SKY_LINE_CATALOG` on page 87 for more details.

## Spatial curvature calibration

Currently the input curvature model is not aligned to the observed scientific slit spectra. This will be implemented in the next release: in the meantime offsets up to 1 pixel may be observed in the tracing of scientific spectra.

## Flat field correction

`--flatfield`: Apply flat field correction. *Default*: `TRUE`

Setting this parameter makes mandatory to specify a normalised flat field frame (see page 75, entry `MASTER_NORM_FLAT_MOS`). The flat field correction consists in dividing the bias subtracted input scientific frame by the normalised flat field frame.



<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	95 of 132

## Sky subtraction

*--skylocal*: Subtract sky spectrum from CCD scientific data. *Default*: TRUE

The local sky subtraction consists on modeling the sky trend for each column of pixels for each spectrum on the CCD.<sup>41</sup> The advantage of this method is that the signal is not resampled before the sky is subtracted, reducing in this way the problems related to small-scale interpolation.

A `MAPPED_SKY_SCI_MOS` (page 90) is produced in this case. Note that global and median sky subtractions cannot be used if the local sky subtraction is applied.

Note however that this method does not apply well to curved or tilted slits: in such case, the *--skymedian* option should be preferred. It is for this reason that, in case of long-slit data *--skylocal* option is not implemented, and it's an alias to the *--skymedian* option.

*--skymedian*: Subtract sky spectrum from rectified scientific data. *Default*: FALSE

The median sky subtraction consists on subtracting a median value of the sky for each wavelength pixel of each rectified slit spectrum.<sup>42</sup>

In general the subtraction of a rectified sky spectrum from rectified data does not give the best results, and in almost all cases the local sky subtraction (see parameter *--skylocal*) should be preferred.

A `MAPPED_SKY_SCI_MOS` (page 90) is produced in this case. Note that global and median sky subtractions are not mutually exclusive.

*--skyglobal*: Subtract global sky spectrum from CCD. *Default*: FALSE

In general the subtraction of a global sky spectrum does not give the best results, because the spectral resolution may vary significantly with the position on the CCD. However this operation may turn out to be useful in case either a local or a median sky subtraction would actually destroy spectra from extended objects that fill all, or almost all, the extension of a slit. See entries `UNMAPPED_SKY_SCI_MOS` and `GLOBAL_SKY_SPECTRUM_MOS` on page 93 for more details.

*--cosmics*: Eliminate cosmic rays hits. *Default*: FALSE

If this parameter is set, then either the local or the global sky subtraction must be requested (see parameters *--skylocal* and *--skyglobal*). Cosmic rays cleaning is almost always superfluous, and should be viewed as mere cosmetics applied to the extracted slit spectra (see entry `MAPPED_SCI_MOS`, page 90). Cosmic ray hits are removed anyway by the optimal extraction procedure of the detected objects.

## Objects detection and extraction

*--dispersion*: Resampling step for rectified and wavelength calibrated spectra. *Default*: 0.0 Å/pixel

This parameter is mandatory (using the default 0.0 would generate an error message). The default value for this parameter, depending on the applied grism, is included in the `GRISM_TABLE` (see page 43): this

<sup>41</sup>This is an iterative process: initially the sky trend is estimated with a robust linear fitting, then outliers (e.g., objects) are rejected, and according to the slit length the sky is trended using a 2nd degree polynomial.

<sup>42</sup>This is an iterative process: initially the sky is estimated as the median value of all the pixels at the same wavelength, then this first estimation of the sky is subtracted, and the objects are detected; finally the median level is evaluated only on pixels outside the object detection spatial interval.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	96 of 132

value is the same that was used by the pattern-matching task for the reference lines identification, which is very close to the mean spectral dispersion (see Section 9.7.3, page 80). It is however possible to specify here any resampling step, if it is found more appropriate: in some extreme cases to resample the signal at a higher resolution may be essential to prevent information loss. To undersample the signal, on the other side, is never advisable (and it makes ineffective the flux conservation correction – see the *flux correction* section ahead).

The products which are directly affected by the `--dispersion` parameter are the following:

- GLOBAL\_SKY\_SPECTR UM\_MOS,
- MAPPED\_ALL\_SCI\_MOS,
- MAPPED\_SCI\_MOS,
- MAPPED\_SKY\_SCI\_MOS,
- REDUCED\_ERROR\_SCI\_MOS,
- REDUCED\_SCI\_MOS, and,
- REDUCED\_SKY\_SCI\_MOS.

Note that the `--dispersion` value must refer to the real CCD pixel size: the given value of the resampling step is internally multiplied by the rebin factor, to match the real pixel size of the input data.<sup>43</sup> In this way the value of the resampling step is made independent from the CCD reading mode, guaranteeing that the same supersampling factor is always applied.

`--startwavelength`: Start wavelength in spectral extraction. *Default*: 0.0 Ångstrom

See the `--endwavelength` parameter

`--endwavelength`: End wavelength in spectral extraction. *Default*: 0.0 Ångstrom

This parameter, together with the `--startwavelength` parameter, defines the wavelength interval to be extracted. Optimal values of the extraction interval, depending on the applied grism, are included in the GRISM\_TABLE (see page 43). Both `--startwavelength` and `--endwavelength` must be otherwise specified (leaving them to 0.0 would generate an error message). It is generally not advisable to specify an extraction interval that is wider than the calibrated interval.

`--slit_margin`: Spectrum edge pixels to exclude from object search. *Default*: 3 (rebinned) pixel

The object detection task will reject objects that are detected too close to the edges of a slit spectrum. There might be different reasons for this, such as objects would be truncated, too close to a confusion region, etc.

`--ext_radius`: Maximum extraction radius for detected objects. *Default*: 6 (rebinned) pixel

The default value is generally good when dealing with point-like objects, but it should be adapted to the size of more extended objects when necessary. Large values of the extraction radius would not harm the extraction quality if an optimal extraction algorithm is applied, but may have devastating effects on the results of a simple aperture extraction. The applied extraction interval is reduced in case nearby objects are detected: an intermediate position between two objects, computed according to the objects luminosity ratio, is never passed.

<sup>43</sup>The rebin factor along the dispersion direction is written to the FITS header keyword ESO DET WIN1 BINX.



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	97 of 132

*--cont\_radius*: Contaminationradius. *Default*: 0 pixel

This parameter may help to prevent the extraction of contaminated objects. The contamination radius is the minimum distance at which two point-like objects of equal luminosity are assumed not to contaminate each other. For two objects having different luminosities the reciprocal contamination distances depend on their luminosity ratio. Indicating with  $L_o$  the peak value of one object integrated spatial profile and with  $L$  the peak value of a nearby object, the quantity

$$S = C \cdot \left( \frac{L}{L_o} \right)$$

is computed, where  $C$  is the specified contamination radius. If the distance between the two objects is less than  $S$ , the examined object is flagged as contaminated and is not extracted. This empirical formula has the effect of assigning a larger contamination radius to relatively brighter objects with respect to dimmer ones.

*--ext\_mode*: Object extraction method. *Default*: 1

Only two methods are currently available for spectral extraction: *--ext\_mode* = 0 corresponds to simple aperture extraction, while *--ext\_mode* = 1 applies Horne's optimal extraction [23].

## Flux calibration

*--flux*: Apply flux conservation factors. *Default*: TRUE

The flux conservation factors applied to the rebinned and extracted slit and object spectra is the ratio between the resampling step and the original signal sampling, along both the spatial and the dispersion directions.<sup>44</sup>

*--time\_normalise*: Apply exposure time normalisation to relevant products. *Default*: TRUE

The following products are affected by this parameter:

- GLOBAL\_SKY\_SPECTR UM\_MOS,
- MAPPED\_ALL\_SCI\_MOS,
- MAPPED\_SCI\_MOS,
- MAPPED\_SKY\_SCI\_MOS,
- REDUCED\_ERROR\_SCI\_MOS,
- REDUCED\_SCI\_MOS,
- REDUCED\_SKY\_SCI\_MOS.
- UNMAPPED\_SCI\_MOS, and,
- UNMAPPED\_SKY\_SCI\_MOS.

*--response*: Order of polynomial modeling the instrument response. *Default*: 5

See Section 10.4, page 108, for the meaning of this parameter

<sup>44</sup>In order to have a view of the flux conservation correction, it is possible to run the *efosc\_science* recipe twice, first setting *--flux* = FALSE and then setting *--flux* = TRUE, finally computing the ratio between the corresponding MAPPED\_ALL\_SCI\_MOS product images.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	98 of 132

--photometry: Apply spectrophotometric calibration. *Default:* FALSE

See Section 10.5, page 109, for the meaning of this parameter

--qc: Compute QC1 parameters. *Default:* TRUE

See next Section.

#### 9.8.4 Quality control parameters

Currently the following QC parameters, used by PSO and DPD, are evaluated by the *efosc\_science* recipe in the case of standard star observations.

**QC SPEC EFFICIENCYi:** Efficiency at given wavelength. *Units:* e<sup>-</sup>/photon

The efficiency curve is computed as the ratio between the standard star catalog fluxes converted to photons (per second per Ångström), and the observed standard star spectrum converted to electrons (per second per Ångström). This curve is then smoothed by a heavy median filter and then fitted by a high degree polynomial, to derive a smooth efficiency curve unaffected by local atmospheric absorptions and by uncertainties around lines in the standard star spectral continuum. The values of the efficiency at different wavelengths are read from this smoothed curve. See Section 10.4, page 108, for more details.

**QC SPEC EFFICIENCYi LAMBDA:** Wavelength at which the efficiency was measured. *Units* Ångström

#### 9.9 efosc\_extract

This recipe is used for reducing scientific spectra. It is identical to the recipe *efosc\_science*, with the only difference that a GLOBAL\_DISTORTION\_TABLE (see page 44) is required in input instead of the DISP\_COEFF\_MOS, CURV\_COEFF\_MOS, and SLIT\_LOCATION\_MOS tables (see pages 71, 72, and 77). This recipe is necessary for on-line data reduction on La Silla, where the extraction mask computed with the recipe *efosc\_calib* may not be immediately available: in this case a general spectral distortion description must be used to generate the appropriate standard extraction mask for any slits configuration. The results are often less accurate than those obtained with the *efosc\_science* recipe, but *efosc\_extract* may turn out to be occasionally very useful for recovering possible failures of the standard data reduction procedure.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	99 of 132

## 10 Algorithms

The data reduction procedures applied by the pipeline recipes currently in use (see Section 8) are described here in some detail.

### 10.1 Propagation of photonic and readout noise

The imaging data reduction of the EFOSC pipeline is characterised by a complete propagation of photonic noise and CCD readout noise to all of its products. In particular, all the image products consist of a FITS file containing two images: the pixel data values are included in the FITS primary array, while the statistical error at each pixel is included in the FITS first extension. Errors are propagated using the error propagation formula in the approximation of gaussian statistics (see also Section 10.2.1, page 100 about this topic). For example, if  $D$  is the value of a pixel  $(x, y)$  in a raw frame, and  $B$  the corresponding value of the bias master calibration frame, the resulting bias subtracted value will be

$$S = D - B$$

The corresponding error, keeping into account the contribution of the readout noise  $r$  (read from the header keyword ESO DET OUT1 RON and converted to ADU), is computed as

$$\Delta S = \sqrt{r^2 + (\Delta B)^2 + \frac{D - B}{g}}$$

where  $g$  is the gain in  $e^-/\text{ADU}$  and  $\Delta B$  is the (propagated) error of the master bias value. With regard to different techniques of image stacking, in the case of the average, the minmax rejection, and the k-sigma clipping methods the stacked frame error is computed as

$$\Delta S = \sqrt{\frac{\sum_i (\Delta S_i)^2}{N}}$$

where  $N$  is the number of non-rejected values. In the case of median stacking the error is computed as

$$\Delta S = f(N) \sqrt{\frac{\sum_i (\Delta S_i)^2}{N}}$$

where  $f(N)$  is 1 for  $N \leq 2$ , and it converges towards  $\sqrt{\pi/2}$  for  $N \rightarrow \infty$ .

In the case of the spectral data reduction (performed with the recipes *efosc\_calib* and *efosc\_science*), errors are just estimated on the final products of the *efosc\_science* recipe. This implies that the errors introduced by both flat fielding and master bias subtraction are neglected, which is generally justifiable. Assuming straightforwardly that  $(\Delta B)^2 \ll r^2$ , the error contribution from flat fielding can be shown to be negligible as well. The noise of a flat field signal  $F$  is given by the usual

$$\Delta F = \sqrt{r^2 + \frac{F}{g}}$$

If  $N$  flat field exposures are stacked, the error on the mean signal will be

$$\Delta F = \sqrt{\frac{r^2 + \frac{F}{g}}{N}}$$

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	100 of 132

Normalizing the signal to a locally smoothed level  $\bar{F}$ , the error on  $f = F/\bar{F}$  would as well scale down to

$$\Delta f = \frac{1}{\bar{F}} \sqrt{\frac{r^2 + \frac{F}{g}}{N}} \simeq \sqrt{\frac{1}{FNg}}$$

because  $F \simeq \bar{F}$ , and the term  $(r/F)^2$  can be safely ignored.

The flat field corrected signal is  $S = (D - B)/f$ . Propagating errors it can be derived

$$\Delta S = \sqrt{\frac{1}{f} \left( r^2 + \frac{D - B}{g} \right) + \frac{1}{f^4} \frac{1}{FNg}}$$

Since  $f \simeq 1$ , and  $FNg$  is a very large number, the error on  $S$  can also be written

$$\Delta S = \sqrt{r^2 + \frac{D - B}{g}} \simeq \sqrt{r^2 + \frac{S}{g}}$$

because  $S \simeq D - B$ . And this is exactly the expression used for the error estimation on spectral data.

The variance of the optimally extracted object spectra is determined as in [23], i.e. as the inverse of the sum of the optimal weights. Such error is further propagated to the measured polarimetric parameters derived by the appropriate combination of extracted spectra, in the case of polarimetric data.

## 10.2 Frame zeropoint computation

It may appear puzzling that in the aligned photometric table (ALIGNED\_PHOT product, see page 62), which reports the zeropoint estimates for each detected standard star, some of the optimal weights (listed in column **weight**) may be negative. How is it possible that an optimally weighted average, as applied for the estimation of the frame zeropoint, would include negative weights?

In order to answer this question, a brief recap of error propagation may be in order.

### 10.2.1 Error propagation in a nutshell

If a quantity  $y$  is a function of  $n$  independent variables  $x_i$

$$y = y(x_1, x_2, \dots, x_n)$$

the variance of  $y$ ,  $(\Delta y)^2$ , can be derived from the variances of the independent variables applying the usual formula for error propagation

$$(\Delta y)^2 = \sum_{i=1}^n \left( \frac{\partial y}{\partial x_i} \right)^2 (\Delta x_i)^2$$

However, this is valid as long as the variables  $x_i$  are independent from each other: if the variable  $x_i$  correlates with the variable  $x_j$ , then their covariance

$$C_{ij} = \text{cov}(x_i, x_j)$$

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	101 of 132

will be different from zero (by definition). In this case not just the variances but also the covariances of the independent variables  $x_i$  must be propagated. Variances and covariances are collected in the  $n \times n$  covariance matrix  $\mathbf{C}$ . The variances lie on the diagonal of the matrix, since

$$C_{ii} = \text{cov}(x_i, x_i) = \text{var}(x_i) = (\Delta x_i)^2$$

Moreover  $\mathbf{C}$  is a symmetric matrix, because

$$C_{ij} = \text{cov}(x_i, x_j) = \text{cov}(x_j, x_i) = C_{ji}$$

With non-diagonal elements different from zero, the full expression for the error propagation is

$$(\Delta y)^2 = \sum_{i=1}^n \sum_{j=1}^n \frac{\partial y}{\partial x_i} \frac{\partial y}{\partial x_j} C_{ij}$$

which turns into the usual formula in case the covariance matrix  $\mathbf{C}$  were diagonal.

To further generalise, let us now suppose to have  $m$  quantities  $y_k$  ( $1 \leq k \leq m$ ), depending on  $n$  values  $x_i$  ( $1 \leq i \leq n$ ). In this case propagating errors means to transform the covariance matrix  $\mathbf{C}$ , related to the  $x_i$ , into the covariance matrix  $\mathbf{G}$  related to the  $y_k$ . This is obtained by applying the most general form of the error propagation,

$$G_{kl} = \sum_{i=1}^n \sum_{j=1}^n \frac{\partial y_k}{\partial x_i} \frac{\partial y_l}{\partial x_j} C_{ij}$$

where

$$G_{kl} = \text{cov}(y_k, y_l)$$

and

$$G_{kk} = \text{var}(y_k) = (\Delta y_k)^2$$

for the diagonal terms. In matrix notation, if  $\mathbf{J}$  is the Jacobian of the transformation from the  $x$ 's to the  $y$ 's

$$J_{ij} = \frac{\partial y_i}{\partial x_j}$$

the error propagation formula is a transformation of the covariance matrix:

$$\mathbf{G} = \mathbf{J} \mathbf{C} \mathbf{J}^T$$

The covariance matrix  $\mathbf{G}$  is the one to apply for further error propagation into new quantities computed in terms of  $y_k$ 's. In summary, error propagation is nothing but the covariance matrix propagation.<sup>45</sup>

Note that in the special case  $\mathbf{C}$  were diagonal,  $\mathbf{G}$  might still contain non-diagonal elements. The formula to apply would become

$$G_{kl} = \sum_{i=1}^n \frac{\partial y_k}{\partial x_i} \frac{\partial y_l}{\partial x_i} (\Delta x_i)^2$$

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<sup>45</sup>This statement is valid under the assumption that the first order derivatives of the transformation are all that is needed for propagating errors. The error propagation formula is derived by Taylor expansion of the transformation, where higher order terms are neglected.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	102 of 132

If both  $y_k$  and  $y_l$  (with  $k \neq l$ ) are a function of  $x_i$ , then then both derivatives  $\frac{\partial y_k}{\partial x_i}$  and  $\frac{\partial y_l}{\partial x_i}$  would be different from zero, and therefore the covariance  $G_{kl}$  would be different from zero too. This is indeed what is expected: if both  $y_k$  and  $y_l$  share one or more common terms, they would turn out to be correlated.

This is exactly the case in the problem of zeropoint computation, where the zeropoints derived for each photometric standard star are indeed based on a number of shared quantities, such as the assumed atmospheric extinction coefficient  $E$  and the linear color correction term  $\Gamma$ , which are considered valid for all stars (see table 9.5.1, page 61, for a list of the quantities used in the zeropoint determination).

**An example** may be useful to clarify how to propagate errors of correlated quantities.

Let us consider the transformation

$$\begin{aligned} F_1 &= ma_1 \\ F_2 &= ma_2 \end{aligned}$$

In this case the quantities  $F_1$  and  $F_2$  depend (as a whole) on the quantities  $a_1$ ,  $a_2$ , and  $m$ . Since  $m$  is shared by the two equations,  $F_1$  and  $F_2$  will be correlated. Assuming that  $a_1$ ,  $a_2$ , and  $m$  are independent quantities, it is easy to determine the variance of  $F_1$  and  $F_2$  applying the usual

$$\begin{aligned} (\Delta F_1)^2 &= \left(\frac{\partial F_1}{\partial a_1}\right)(\Delta a_1)^2 + \left(\frac{\partial F_1}{\partial m}\right)(\Delta m)^2 \\ (\Delta F_2)^2 &= \left(\frac{\partial F_2}{\partial a_2}\right)(\Delta a_2)^2 + \left(\frac{\partial F_2}{\partial m}\right)(\Delta m)^2 \end{aligned}$$

that is

$$\begin{aligned} (\Delta F_1)^2 &= m^2(\Delta a_1)^2 + a_1^2(\Delta m)^2 \\ (\Delta F_2)^2 &= m^2(\Delta a_2)^2 + a_2^2(\Delta m)^2 \end{aligned}$$

However, if the quantities  $F_1$  and  $F_2$  are used in a further transformation – for instance, to derive a quantity  $F$  corresponding to their sum

$$F = F_1 + F_2$$

the knowledge of the errors  $\Delta F_1$  and  $\Delta F_2$  is not enough to determine the error  $\Delta F$ : also the covariances are needed, because the quantities  $F_1$  and  $F_2$  are correlated.

It is therefore necessary to transform the covariance matrix  $\mathbf{C}$  of the quantities  $a_1$ ,  $a_2$ , and  $m$  into the covariance matrix of the quantities  $F_1$  and  $F_2$ . As shown, this is done by applying the  $\mathbf{G} = \mathbf{J}\mathbf{C}\mathbf{J}^T$ , where  $\mathbf{J}$  is the Jacobian of the transformation from  $(a_1, a_2, m)$  to  $(F_1, F_2)$ . In this specific case, since  $a_1$ ,  $a_2$ , and  $m$  are independent, their covariance matrix is diagonal and includes only variances:

$$\mathbf{C} = \begin{pmatrix} (\Delta a_1)^2 & 0 & 0 \\ 0 & (\Delta a_2)^2 & 0 \\ 0 & 0 & (\Delta m)^2 \end{pmatrix}$$

The Jacobian of the transformation is given by

$$\mathbf{J} = \begin{pmatrix} \frac{\partial F_1}{\partial a_1} & \frac{\partial F_1}{\partial a_2} & \frac{\partial F_1}{\partial m} \\ \frac{\partial F_2}{\partial a_1} & \frac{\partial F_2}{\partial a_2} & \frac{\partial F_2}{\partial m} \end{pmatrix} = \begin{pmatrix} m & 0 & a_1 \\ 0 & m & a_2 \end{pmatrix}$$

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	103 of 132

Hence the covariance matrix of  $(F_1, F_2)$  is

$$\mathbf{G} = \mathbf{J}\mathbf{C}\mathbf{J}^T = \begin{pmatrix} m^2(\Delta a_1)^2 + a_1^2(\Delta m)^2 & a_1 a_2(\Delta m)^2 \\ a_1 a_2(\Delta m)^2 & m^2(\Delta a_2)^2 + a_2^2(\Delta m)^2 \end{pmatrix} = \begin{pmatrix} (\Delta F_1)^2 & a_1 a_2(\Delta m)^2 \\ a_1 a_2(\Delta m)^2 & (\Delta F_2)^2 \end{pmatrix}$$

Its diagonal terms are, as expected, the variances already found above applying the usual error propagation formula. The matrix  $\mathbf{G}$  can now be used to derive the error on any quantity based on  $(F_1, F_2)$ . For instance, if such quantity is  $F = F_1 + F_2$ , then the generic

$$(\Delta F)^2 = \sum_{i=1}^2 \sum_{j=1}^2 \frac{\partial F}{\partial F_i} \frac{\partial F}{\partial F_j} G_{ij}$$

becomes

$$(\Delta F)^2 = (\Delta F_1)^2 + (\Delta F_2)^2 + 2a_1 a_2(\Delta m)^2$$

If  $F_1$  and  $F_2$  were statistically independent the variance of  $F$  would simply be the sum of the variances of  $F_1$  and  $F_2$ : however in this case the statistical correlation leads to a greater variance, by the additional term  $2a_1 a_2(\Delta m)^2$ . Only in case  $m$  were errorless ( $\Delta m = 0$ ) there would be no correlation.

Naturally, this result would have also been obtained by directly applying the usual error propagation formula to  $F = m a_1 + m a_2$ . In simple cases such this one there is no need to get all the way to propagating covariance matrices, but when dealing with a larger or unknown number of variables it is safer and more convenient to use the covariance matrix and matrix algebra in error propagation.

### 10.2.2 Optimally weighted average

In order to estimate the frame zeropoint, a weighted average of the single zeropoints (computed for each identified standard star) is performed. The question is: what are the weights that would make for an *optimal* linear estimator? In other words, what is the best linear estimator that would minimise the variance of the estimated quantity? Typically the answer would be: each contributing quantity should be weighted by the inverse of its variance. However, this is only true for uncorrelated quantities. The individual zeropoints are correlated quantities, because they all depend on the same estimate of the atmospheric extinction, of the color correction term, and of the airmass.

It is very simple to determine the optimal weights leading to the best estimate,  $y$ , from the correlated quantities  $x_i$ : it is sufficient to apply the error propagation formula to the general expression of the weighted average

$$y = \frac{\sum_i \omega_i x_i}{\sum_i \omega_i}$$

As seen in the previous Section, the variance of the average is given by

$$\begin{aligned} (\Delta y)^2 &= \sum_i \sum_j \frac{\partial y}{\partial x_i} \frac{\partial y}{\partial x_j} C_{ij} \\ &= \sum_i \sum_j \frac{w_i}{\sum_k \omega_k} \frac{w_j}{\sum_k \omega_k} C_{ij} \\ &= \frac{1}{(\sum_k \omega_k)^2} \sum_i \sum_j \omega_i \omega_j C_{ij} \end{aligned}$$

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	104 of 132

Minimum variance is reached where all its partial derivatives are zero:

$$\frac{\partial(\Delta y)^2}{\partial \omega_l} = \frac{2}{(\sum_k \omega_k)^2} \sum_i \omega_i C_{li} - \frac{2}{(\sum_k \omega_k)^3} \sum_i \sum_j \omega_i \omega_j C_{ij} = 0$$

that is

$$\sum_i \omega_i C_{li} = \frac{\sum_i \sum_j \omega_i \omega_j C_{ij}}{\sum_i \omega_i}$$

Setting  $A_j = \sum_i \omega_i C_{ij}$  this relation becomes

$$A_l = \frac{\sum_i \omega_i A_i}{\sum_i \omega_i}$$

This shows that  $A_l$  is independent on  $l$ . The constancy of  $A_l$  is the condition to be fulfilled by optimal weights. Since only the relative weights are significant,  $A_l$  can be set to any arbitrary constant, and for simplicity it is set to 1:

$$\sum_i \omega_i C_{ij} = 1$$

Solving this system of linear equations is of course only possible if the covariance matrix  $\mathbf{C}$  is invertible (which is generally the case). It can be noted that, in case the averaged quantities were statistically independent,  $\mathbf{C}$  would be diagonal and the linear system would be promptly solved:

$$\omega_j = \frac{1}{C_{jj}} = \frac{1}{(\Delta x_j)^2}$$

which is the well known inverse-of-the-variance rule. The generic linear system can be written in matrix notation

$$\mathbf{C}\mathbf{w} = \mathbf{1}$$

where  $\mathbf{w}$  is the vector of the optimal weights, and  $\mathbf{1}$  a vector whose elements are all 1s. The solution is

$$\mathbf{w} = \mathbf{C}^{-1}\mathbf{1}$$

that is, the  $j$ -th weight is given by the sum along the  $j$ -th row (or column, since  $\mathbf{C}^{-1}$  is symmetric) of the inverse of the covariance matrix

$$\omega_j = \sum_i C_{ij}^{-1}$$

This result can also be derived from first principles (without assuming any particular functional form of the estimator) by considering  $n$  correlated normally distributed random variables  $\mathbf{x} = (x_1, \dots, x_n)$  with the same expectation value  $y$  (as in the case of individual star zeropoints), and covariance matrix  $\mathbf{C}$ . The maximum likelihood principle can be used to determine which value of  $y$  makes the observed  $\mathbf{x}$  most likely. The likelihood function is just the combined probability density function

$$L(y) = \frac{1}{(2\pi)^{n/2} |\mathbf{C}|^{1/2}} \exp \left( -\frac{1}{2} (\mathbf{x} - y\mathbf{1})^T \mathbf{C}^{-1} (\mathbf{x} - y\mathbf{1}) \right)$$



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	105 of 132

where  $\mathbf{y}$  is the constant vector  $(y, \dots, y)$ . Maximizing  $L$  is equivalent to minimizing

$$\chi^2(y) = -2 \log L = \text{const} + (\mathbf{x} - \mathbf{y})^T \mathbf{C}^{-1} (\mathbf{x} - \mathbf{y}) = \text{const} + \sum_{ij} (x_i - y) C_{ij}^{-1} (x_j - y)$$

which has derivative

$$\frac{d\chi^2}{dy} = \sum_{ij} 1 \times C_{ij}^{-1} (x_j - y) + \sum_{ij} (x_i - y) C_{ij}^{-1} \times 1$$

By relabelling summation indices  $ij$  and noting that  $\mathbf{C}^{-1}$  is symmetric, we see that the two sums are equal, so the optimal estimate is given by

$$0 = \sum_{ij} C_{ij}^{-1} (x_i - y) = \sum_{ij} C_{ij}^{-1} x_i - \sum_{ij} C_{ij}^{-1} y,$$

or

$$y = \frac{\sum_{ij} C_{ij}^{-1} x_i}{\sum_{ij} C_{ij}^{-1}}$$

which is a weighted average with weights

$$\omega_i = \sum_j C_{ij}^{-1}$$

as before. It can be easily shown, by replacing this solution in the general expression of the variance  $(\Delta y)^2$ , that the variance of the optimal average is simply the inverse of the sum of all weights, which is also the sum of all the elements of the matrix  $\mathbf{C}^{-1}$ :

$$(\Delta y)^2 = \frac{1}{\sum_i \omega_i} = \frac{1}{\sum_{ij} C_{ij}^{-1}}$$

Hence it appears that the sum of all the optimal weights must always be positive. However, within this constraint, nothing forbids that *some* of the weights could be negative. But would this happen with real data?

The answer is yes. A covariance matrix is always a positive definite matrix: when it is diagonalised, its diagonal would just be made of variances which are by definition positive. This proves that the covariance matrix has only positive *eigenvalues*, and therefore must be positive definite. This just means that the error ellipsoid has always positive main axes, which is no big news. The inverse is also true: any positive definite matrix is also a possible covariance matrix (i.e., any ellipsoid represents a realistic uncertainty region). Within such conditions, it can be shown that negative weights are still a possibility: for instance, the following  $2 \times 2$  covariance matrix

$$\mathbf{C} = \begin{pmatrix} 1.20 & 1.00 \\ 1.00 & 0.90 \end{pmatrix}$$

has eigenvalues 0.0388 and 2.061, so it is positive definite. The inverse is

$$\mathbf{C}^{-1} = \begin{pmatrix} 11.25 & -12.50 \\ -12.50 & 15.00 \end{pmatrix}$$

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	106 of 132

The optimal weights are therefore  $\omega_1 = -1.25$  and  $\omega_2 = 2.50$ . Even though their sum is positive, one of the weights is negative.

What is the physical meaning of negative weights? Typically a weight is perceived as a measure of the "importance" of a quantity in the computation of a weighted average: a high weight means that a contribution counts a lot, while a zero weight means that a contribution does not count at all. A negative weight implies that a contribution counts, but negatively. This means that the optimal average of two values *may not lie between the values themselves*. What is happening in practice is that, when the variances of the contributing quantities are not enough to explain the observed variation, then the scatter can only be explained by the covariances.

To better clarify this, let us consider the case of the frame mean zeropoint computation: after applying the color term and the atmospheric extinction corrections to the instrumental magnitudes, the individual zeropoints derived for each standard star should ideally be all identical (if they were not expected to be identical, it would not make sense to average them). However, because of statistical errors, the single zeropoints will differ from each other. The optimal average represents the best estimator of the true zeropoint, because it tries to minimize the variance of the estimate. There are two ways to do that, and both are (implicitly) applied by the optimal estimator:

1. assign smaller weights to zeropoints with greater statistical uncertainty, and
2. minimise the scatter due to possible systematic errors.

Indeed, since the single zeropoints are based on the same color term and atmospheric extinction coefficients, the random error of such common quantities acts like a systematic error affecting all the computed zeropoints. This systematic error can be reduced by finding values for the color term and the atmospheric extinction coefficients which would reduce the scatter of the averaged zeropoints. This is what is implicitly offset by a negative weight: when the zeropoints of two different stars differ more than it could be likely expected from their variances, it is probably because the color correction was biased by an inaccurate color correction term. Modifying appropriately the color term would modify the zeropoints of *both* stars - which is how the best estimate of the mean zeropoint may happen to lie outside the interval between the contributing values.

### 10.3 The efosc\_photometry recipe

As seen in Section 9.6, page 65, the general model for the corrected instrumental magnitude  $m_{ij}$  of star  $i$  on exposure  $j$  is

$$M_i - \Gamma \cdot C_i + p(A_j, C_i) + E_j A_j - Z + f(x_{ij}, y_{ij}) = m_{ij}$$

where the symbols are consistent with table 9.5.1 (page 61),  $x$  and  $y$  are coordinates on the detector, and non-linear dependencies are accounted for by the polynomials  $p()$  and  $f()$ . All quantities are referred to the  $i$ -th star in the  $j$ -th exposure as indicated.

In practice, the equations are solved by moving all assumed (known) terms to the right hand side, and leaving the terms containing free (unknown) parameters on the left hand side. In matrix notation this equation system can be written (as in [28])

$$\mathbf{Ax} = \mathbf{b}$$

where  $\mathbf{x}$  is the vector of unknown parameters,  $\mathbf{A}$  the matrix of their coefficients, and  $\mathbf{b}$  the vector of measurements.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	107 of 132

For example, in the simple model where all  $E_j$  are constrained to be equal to the same (unknown) value  $E$  and all other parameters are assumed (catalog magnitudes, instrument zeropoint  $Z$ , linear color correction term  $\Gamma$ ), and where the non-linear dependencies  $p()$  and  $f()$  are ignored, the equations would become:

$$E = \frac{1}{A_j}(m_{ij} - M_i + \Gamma \cdot C_i + Z)$$

The measurements (on the right hand side) are typically based on common quantities: for instance, the  $i$ -th star may be observed in more than one exposure, and therefore its catalog magnitude and color would be shared among different right hand sides. For this reason the covariance matrix  $\mathbf{C}$  of  $\mathbf{b}$  is generally not diagonal.

In order to solve this equation system, the recipe *efosc\_photometry* computes first the covariance matrix of the right hand side.

By the principle of maximum likelihood, and assuming gaussian errors, the  $\chi$ -squared of the problem is

$$\chi^2 = (\mathbf{b} - \mathbf{Ax})^T \mathbf{C}^{-1} (\mathbf{b} - \mathbf{Ax})$$

From this the minimum  $\chi$ -squared solution for  $\mathbf{x}$  is derived by setting  $d\chi^2/d\mathbf{x} = 0$ :

$$\mathbf{A}^T \mathbf{C}^{-1} \mathbf{Ax} = \mathbf{A}^T \mathbf{C}^{-1} \mathbf{b}$$

The minimum  $\chi$ -squared solution is therefore

$$\mathbf{x} = (\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{C}^{-1} \mathbf{b}$$

and is obtained by Cholesky-decomposition of  $\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A}$  <sup>46</sup>. The overall execution time is  $O(n^3)$  (where  $n$  is the number of equations) and dominated by the computation of  $\mathbf{C}^{-1}$ . The errors on the solution are derived by propagating the errors of  $\mathbf{b}$  to  $\mathbf{x}$ .  $(\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A})^{-1}$  is the covariance matrix of  $\mathbf{x}$ ,  $\mathbf{C}_x$ : in the transformation from  $\mathbf{b}$  to  $\mathbf{x}$

$$\mathbf{J} = (\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{C}^{-1}$$

is clearly the Jacobian of the transformation. Computing the covariance matrix of  $\mathbf{x}$  from the covariance matrix of  $\mathbf{b}$  using the error propagation formula (see Section 10.2.1, page 100) leads to:

$$\begin{aligned} \mathbf{C}_x &= \mathbf{J} \mathbf{C} \mathbf{J}^T \\ &= (\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{C}^{-1} \mathbf{C} (\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{C}^{-1} \\ &= (\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A})^{-1} \end{aligned}$$

Note that, in the special case where  $\mathbf{C}$  is diagonal, the solutions for  $\mathbf{x}$  and  $\mathbf{C}_x$  reduce to the solutions for the general linear weighted least squares problem [29].

Naturally, it may happen that the equation system remains underdetermined — trying to fit an atmospheric extinction coefficient  $E_j$  for each single frame when also  $Z$  is left free would be one of such cases, because the terms  $E_j A_j$  would degenerate with  $Z$ .

<sup>46</sup>In [28] singular value decomposition (SVD) is used

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	108 of 132

## 10.4 Determination of spectral response and efficiency curves

The efficiency of an instrument is defined as the ratio between detected photons and incoming photons, and can be derived by comparing the observed fluxes with the tabulated fluxes of known objects.

The spectral efficiency can be obtained with the recipe *efosc\_science* (see Section 9.8, page 86) applied to a standard star observation.

The extracted standard star spectrum,  $X(\lambda)$  is converted into  $e^- s^{-1} \text{\AA}^{-1}$ :

$$S(\lambda) = \frac{g X(\lambda)}{t \Delta\lambda}$$

where  $g$  is the gain factor in  $e^- / \text{ADU}$ ,  $t$  the exposure time in seconds, and  $\Delta\lambda$  the constant wavelength step at which the spectrum was resampled after its calibration in wavelength.

The magnitude losses  $\Delta m(\lambda)$  listed in the column `EXTINCTION` of the atmospheric extinction table (see Section 7.6, page 45) are turned into flux losses, and applied to the observed spectrum:

$$S_o(\lambda) = S(\lambda) 10^{0.4 a \Delta m(\lambda)}$$

where  $S_o(\lambda)$  is the spectrum at airmass zero and  $a$  is the airmass of the standard star observation. The values of the atmospheric extinction are linearly interpolated from the tabulated values for all the wavelength of the observed spectrum. At those wavelengths where no atmospheric extinction data are available,  $S_o(\lambda)$  is set to zero.

The standard star catalog fluxes  $C(\lambda)$ , given in  $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1} 10^{-16}$  in the `STD_FLUX_TABLE` (see Section 7.7, page 45), are converted into photons collected by the telescope using

$$F(\lambda) = C(\lambda) \frac{A_t}{h\nu}$$

Considering  $A_t = 9.01 \cdot 10^4 \text{ cm}^2$  the VLT efficient area, and  $hc = 1.98 \cdot 10^{-8} \text{ erg \AA}$ , one derives

$$F(\lambda) = 4.55 \cdot 10^{-4} C(\lambda) \lambda$$

(expressed in  $\text{photons s}^{-1} \text{\AA}^{-1}$ , as the  $10^{-16}$  factor is included in the numeric part). The efficiency is finally computed as

$$E(\lambda) = \frac{S_o(\lambda)}{F(\lambda)}$$

(electrons per photon).

The efficiency  $E(\lambda)$  is set to zero at those wavelengths where no standard star catalog fluxes are available, and is written to the column `RAW_EFFICIENCY` of the output spectro-photometric table (see Table 9.8.2, page 92).

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	109 of 132

The response curve used in the flux calibration of observed scientific spectra (see next Section) is obtained by:

$$R(\lambda) = \frac{C(\lambda)}{S_o(\lambda)}$$

$R(\lambda)$  is set to zero where no standardstar catalog fluxes are available, and is written to the column `RAW_RESPONSE` of the output spectro-photometric table.

As a final step, both  $E(\lambda)$  and  $R(\lambda)$  are passed with a very broad median filter and finally fit by a high degree polynomial, in order to derive a heavily smoothed version of the curves.<sup>47</sup> The smoothed curves are written as well to the output spectro-photometric table, at the columns `EFFICIENCY` and `RESPONSE`.

## 10.5 Spectrophotometric calibration

Scientific spectra extracted by the recipe *efosc\_science* can be calibrated in flux by specifying an atmospheric extinction table (see Section 7.6, page 45), and an appropriate spectro-photometric table (see `SPECPHOT_TABLE`, page 92). The spectro-photometric table can be produced by the recipe *efosc\_science* itself (see Section 9.8, page 86)

## 10.6 Overview of the spectral self-calibration procedure

A more detailed description of the instrument-independent tasks involved in the complete self-calibration procedure is given in the next sections. Here is just provided an overview, which is useful for setting the individual tasks in their appropriate context.

1. Retrieve from the reference arc lamp line catalog the line pattern to be searched on arc lamp exposures.
2. After bias and background subtraction, examine the arc lamp exposure one column at a time. For each CCD column:
  - (a) Run the 1D peak-detection task, to produce a list of reference arc lamp lines candidates.
  - (b) Run the 1D pattern-recognition task, to select from the list of candidates a list of identified peaks. Not all the arc lamp lines are expected to be always identified, because the spectra are presumably distorted, and some CCD column may cross a spectrum just partially, or even miss it entirely (see Figure 10.6.1).
3. Apply a preliminary wavelength calibration to each CCD column, within the specified wavelength range.
4. Choose the central wavelength of the grism as a reference wavelength.
5. Find the CCD position of each connected region of CCD pixels containing the reference wavelength.
6. Run the 2D pattern-recognition task, to match the physical positions of the slits on the focal plane with the positions found on the CCD for the reference wavelength.

<sup>47</sup>The preliminary median filtering has mainly the purpose to eliminate obvious atmospheric (local) absorption bands, and to give all weight to the spectral continuum of the observed standard star.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	110 of 132

7. If requested, and if there are enough slits, fit a transformation between slits positions and CCD positions, and upgrade the list of reference positions on the CCD.
8. Trace the edges of each flat field spectrum, starting from the found positions of the reference wavelength.
9. Fit the traces with a low-degree polynomial. If requested, and if there are enough slits, fit also a global model of the obtained coefficients.
10. Extract the arc lamp spectra following the determined spatial curvature (interpolating fluxes along the spatial direction). For each row of each arc lamp spectrum:
  - (a) Run the 1D peak-detection task on the extracted spectra, to produce a list of reference arc lamp lines candidates from the *whole* spectral range.
  - (b) Run the 1D pattern-recognition task, using the pattern from the line catalog, to select from the list of candidates a list of identified peaks.
  - (c) Fit a relation between the positions of the identified peaks *vs* the corresponding wavelengths.<sup>48</sup>
11. If requested, and if there are enough slits, fit also a global model of the obtained coefficients, in order to improve the local solutions.

At this point the spectral extraction mask is completely determined, and for each spectrum a specific coordinate system is defined, where to a CCD pixel correspond a wavelength and a position on the telescope focal plane. If the instrument were stable, it would be possible to extract the scientific spectra applying directly this extraction mask. In general, however, the extraction mask obtained from the day calibration exposures should be aligned to the scientific spectra before being applied.

### 10.6.1 1D peak-detection

Many sophisticated methods are available for detecting peaks and determining their positions along a one-dimensional signal. Any one of them is in principle suitable for the 1D peak-detection task of an automatic MOS data reduction pipeline.

The most important thing to note, however, is that on a calibration approach based on pattern-recognition the strongest requirement is that *the searched pattern must be present in the data*.<sup>49</sup>

In a traditional approach, peaks are initially rejected by the peak-detection task (depending on their statistical significance), and finally by the model fitting task (if they are found to be outliers). But in case a pattern-recognition algorithm is applied, the significance of a peak should be primarily judged by its being part of the expected pattern.

For this reason virtually any flux excess – no matter how significant – should be flagged as a peak candidate.

In the specific case of arc lamp spectra, the emission lines are very well exposed, and the S/N ratio of the lines to detect is almost always very high. This makes possible to apply a very simple 1D peak-detection method, based on the following two statements:

---

<sup>48</sup>This is the local wavelength calibration.

<sup>49</sup>Or at least long uninterrupted portions of it.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	111 of 132

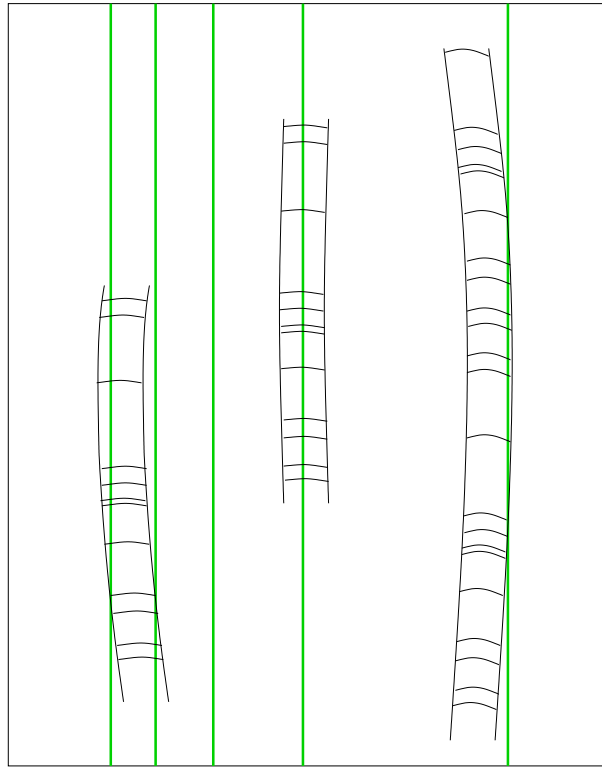


Figure 10.6.1: *CCD columns may not cut the whole range of the raw arc lamp spectra, because the spectra are not read along their curvature. However, even incomplete portions of the searched pattern can be identified by the pattern-matching algorithm.*

**Any local maximum identifies a peak:** in other words, a peak is identified by any pixel that is preceded and is followed by one pixel with a lower value (see Figure 10.6.2 a).

**A peak position is determined by parabolic interpolation of the three found pixel values:** if a local maximum is found, the central pixel and its two neighbours are interpolated by a parabola. The position of the parabola's vertex is taken as the position of the peak (see Figure 10.6.2 b). A peak position is then improved by applying more accurate methods: but if such methods fail, for instance finding positions that are significantly different from the parabolic ones, the original peak position is kept.

Even if obvious background noise fluctuations are excluded from the list of found peaks (e.g., by requiring that the values of the local maxima are greater than a given threshold), it is clear that with this method any contamination, hot pixel, cosmic ray, etc., would be reported as a "peak". This fulfills the critical requirement for the 1D pattern-recognition task reported above (see also Section 10.6.2, page 112).

The position  $x$  of a peak is given by

$$x = x_o + R$$

where  $x_o$  is the (integer) position of the pixel corresponding to a local maximum, and  $R$  the offset corresponding

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	112 of 132

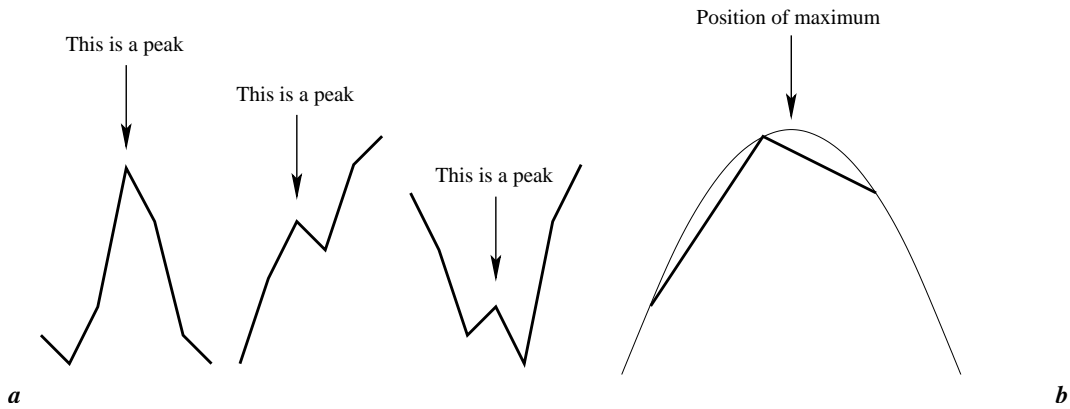


Figure 10.6.2: a) Any local maximum identifies a peak. b) A peak position is determined by parabolic interpolation of three pixel values about the local maximum.

to the position of the maximum obtained by parabolic interpolation:

$$R = \frac{1}{2} \left( \frac{v_1 - v_{-1}}{2v_o - v_1 - v_{-1}} \right)$$

where  $v_{-1}$ ,  $v_o$ , and  $v_1$  are the values of the pixels  $x_o - 1$ ,  $x_o$ , and  $x_o + 1$ , always fulfilling  $v_{-1} \leq v_o$  and  $v_1 < v_o$ , or  $v_{-1} < v_o$  and  $v_1 \leq v_o$  (see Figure 10.6.3).

The quantity  $R$  never diverges, and does not depend on the background level (assuming that the background level is the same for the three pixels).<sup>50</sup>

## 10.6.2 1D pattern-recognition

A simple method for 1D pattern-recognition has been developed in the attempt to increase the robustness of the wavelength calibration, despite possible mechanical instabilities of the instrument.

In order to work, this method just requires a rough expectation value of the spectral dispersion (in Å/pixel), and a line catalog. The line catalog should just include lines that are expected somewhere in the CCD exposure of the calibration lamp.<sup>51</sup>

The line-pattern would be searched in the list of CCD positions of arc lamp lines candidates produced by the 1D peak-detection task (see Section 10.6.1, page 110). Typically, the arc lamp lines candidates will include light contaminations, hot pixels, and other unwanted signal, but only in extreme cases this prevents the pattern-recognition algorithm from identifying all the reference lines. The pattern is detected even in the case the spectra contained more arc lamp lines than actually listed in the input line catalog. In particular, this method is not deceived by spectral multiplexing, even in case of significant spectral overlap: all spectra are identified as separate instances of the same pattern.

<sup>50</sup>In the case of very wide slits, the emission lines profiles display a flat top that would prevent the direct application of this method. This is resolved by the preliminary application of a box filter as wide as the lines widths.

<sup>51</sup>The line catalog represents the pattern that should be searched on the CCD, and adding extra lines would destroy this pattern. Note, however, that a catalog including extra lines at its blue and/or red ends is still allowed.



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	113 of 132

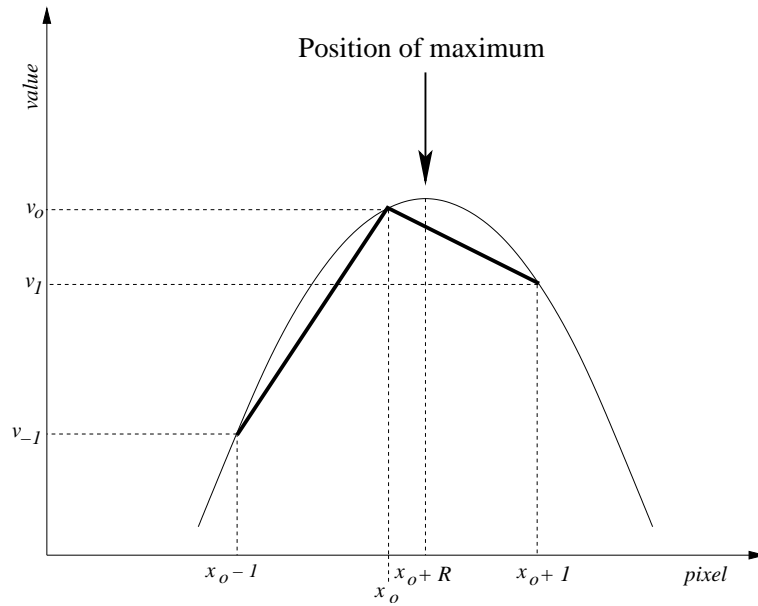


Figure 10.6.3: *Peak position estimate.*

This method is based on the assumption that the relation between wavelengths and CCD positions is with good approximation *locally* linear.<sup>52</sup>

The ratio between consecutive intervals in wavelength and in pixel is invariant to linear transformations and therefore this quantity can be used in the recognition of *local* portions of the searched pattern. All the examined sub-patterns will overlap, leading to the final identification of the whole pattern.

Let be:

$d$ : a rough value of the expected spectral dispersion ( $\text{\AA}/\text{pixel}$ ).

$\Delta d$ : a tolerance value on the expected dispersion, large enough to ensure that, at all wavelengths, the real spectral dispersion will be included in the interval from  $d - \Delta d$  to  $d + \Delta d$ .

$W$ : the number of wavelengths in the input line catalog.

$N$ : the number of detected peaks.<sup>53</sup>

$\lambda_i$ : the  $i$ -th wavelength of the input line catalog, with  $1 \leq i \leq W$ .

$p_j$ : the position of the  $j$ -th peak, with  $1 \leq j \leq N$ .

All the arc lamp wavelengths  $\lambda_i$  are taken one by one, excluding the first and the last wavelengths ( $i = 1$  and  $i = W$ ). The ratio  $R_i$  of the wavelength difference with the preceding and the following wavelength is

<sup>52</sup>This is generally true for modern spectrographs, but if this were not the case the detected peaks positions may be preliminary transformed to roughly approach linearity, before being processed and identified by the pattern-matching task described here.

<sup>53</sup>Note that, as said above, it is typically  $N > W$ , or even  $N \gg W$ .

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	114 of 132

computed:

$$R_i = \frac{\lambda_{i+1} - \lambda_i}{\lambda_i - \lambda_{i-1}}$$

The same ratio is now searched in the list of peak positions: for each  $i$ , all the peak positions  $p_j$  are checked, excluding the first and the last one, taking care however to exclude from the computation any interval that would be incompatible with the expected spectral dispersion. This is done in the following way: for each considered  $p_j$ , the following *forward* search interval  $p_{min}$  to  $p_{max}$  is defined (see Figure 10.6.4):

$$p_{min} = p_j + \frac{\lambda_{i+1} - \lambda_i}{d + \Delta d}$$

$$p_{max} = p_j + \frac{\lambda_{i+1} - \lambda_i}{d - \Delta d}$$

A *backward* search interval is similarly defined:

$$p_{min} = p_j - \frac{\lambda_i - \lambda_{i-1}}{d - \Delta d}$$

$$p_{max} = p_j - \frac{\lambda_i - \lambda_{i-1}}{d + \Delta d}$$

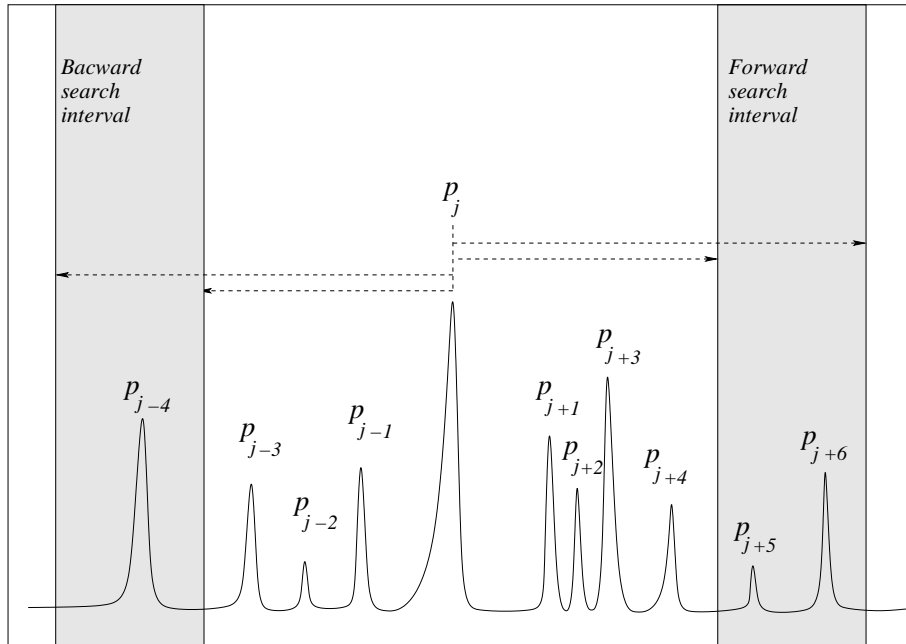


Figure 10.6.4: Given a peak  $p_j$ , a forward and a backward search intervals compatible with an expected value of the spectral dispersion are defined. In this picture, peak positions  $p_{j-4}$ ,  $p_{j+5}$  and  $p_{j+6}$  are used in the computation of the distance ratios to be compared with the wavelength interval ratio  $R_i$ . This process is repeated for each catalog wavelength and for each peak position, accumulating scores that will allow the final peaks identification.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	115 of 132

Any peak position included either in the forward or in the backward search intervals is used for computing a ratio of distances from the position  $p_j$  (analogous to  $R_i$ ). Each time a computed ratio equals  $R_i$ ,<sup>54</sup> the three peak positions used for the computation (one is  $p_j$ , another is one from the backward search interval, and another is one from the forward search interval) are assigned respectively the wavelengths  $\lambda_{i-1}$ ,  $\lambda_i$ , and  $\lambda_{i+1}$ . This assignment is not final: the same wavelength may even be assigned to different peaks, and the same peak may be assigned to different wavelengths. Each time a wavelength is assigned to a peak, a counter is increased, to keep a complete record of the assignments of wavelengths to peaks. Some wavelength assignments might be mistaken, and therefore not confirmed by successive comparisons.<sup>55</sup> The peaks that at the end of the analysis display a high score with respect to a given  $\lambda$  are considered identified, while ambiguous scores are rejected. The identified peaks are submitted to specialised sorting tasks that order them into separate self-consistent sequences (to take care of possible spectral multiplexing). This completes the peak identification process.

This procedure is surprisingly fast, and has been tested successfully with VIMOS spectroscopic data obtained with all the available grisms on all the instrument quadrants, both in MOS and IFU modes (i.e., using 48 independent instrument configurations), as well as all the FORS1 and FORS2 grisms in the LSS, MOS, and MXU instrument modes. All the arc lamp lines listed in the line catalog are correctly identified without relying on a pre-existing instrument distortion modeling.

### 10.6.3 Determination of the spectral range

The spectral extraction range is specified by the user. A default range for each instrument configuration is given in the system configuration files (GRISM\_TABLE, see page 43).

### 10.6.4 Choice of a reference wavelength

The reference wavelength is just an arbitrarily chosen origin for spectral coordinates (both in wavelength and in CCD pixels), used in the definition of the wavelength calibration and of the spatial curvature models. Typically, a reference wavelength may be chosen at the center of the extracted spectral range.

However, if different spectral ranges are specified for the same grism, or if the spectral range is computed automatically (see previous Section), a different reference wavelength might be computed for different data reduction sessions. Because of a need for consistency, for example in instrument health monitoring, the grism central wavelength specified in the FITS headers of the data to be processed is always used.

### 10.6.5 Position of the reference wavelength on the CCD

One of the products of the 1D pattern-recognition task run on the extracted CCD rows (see this Section, page 109) is a boolean image, where all the pixels including the reference wavelength are flagged. After applying morphological operators for reducing the impact of occasional gaps in the data, the baricenter of all the connected regions of flagged pixels is computed. The computed coordinates on the CCD should correspond to

<sup>54</sup>Within a given tolerance: this tolerance should be large enough to account for any deviation of the real wavelength calibration from the local linear approximation. A preposterously large value of 5% is used successfully with all the VIMOS, FORS1/2, and EFOSC2 instrument modes.

<sup>55</sup>Note that each peak is examined more than once, as the loop on wavelengths proceeds, since it may be included in forward and backward search intervals of other peaks.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	116 of 132

the positions of the slit centers on the mask plane. The match between the two sets is determined by the 2D pattern-recognition task (see next Section).

### 10.6.6 2D pattern-recognition

The 2D pattern-recognition method applied here is based on a point-matching algorithm, and it is used for matching positions on the telescope focal plane (mask) with positions on the instrument focal plane (CCD). It will then be possible to determine the transformation between the two coordinate systems, and to match each spectrum with its slit.<sup>56</sup>

Straightforward invariants to translation, rotation, rescaling, and reflection, are distance ratios and angles. In the method described here, distance ratios are preferred, and the reflection-invariance is dropped for reducing the risk of false matches.

For each of the two sets of points – the *pattern* set P, and the *observed* set D – all the possible triangles are constructed. The sides of each triangle are read clockwise,<sup>57</sup> and their lengths  $L_1$ ,  $L_2$ , and  $L_3$  are conventionally listed starting from the longest side (if two sides are equal, the first of the consecutive equal sides is taken). An ordered pair,  $(\alpha, \beta)$ , can be associated to each triangle, with

$$\alpha = \frac{L_2}{L_1} \quad \beta = \frac{L_3}{L_1}$$

Such quantities are used to match similar triangles from both sets. The matches are made by associating nearby points on the  $\alpha - \beta$  plane (see Figure 10.6.5). To each triangle are also assigned the coordinates of their vertices, and the applied normalisation factor  $L_1$ .

Initially, only safe matches are selected, corresponding to  $(\alpha, \beta)$  bins containing just *one* triangle from each of the two input sets.<sup>58</sup> Such matches are used to get a first estimate of the scale factor, that is taken as the median of all the scale factors derived from the pairs of matching triangles,

$$S = \frac{(L_1)_P}{(L_1)_D}$$

At this point the complete list of triangles is revisited, eliminating all the matches that are incompatible with the found scale factor.<sup>59</sup> Finally, a rotation angle is computed for each matching pair, and incompatibilities with the median rotation angle are eliminated as well.

From the surviving triangles a list of matching points can be drawn and the geometrical transformation between the two sets can be determined. With the fitted transformation, points that were possibly lost to the matching procedure may be recovered, and a better transformation obtained from the extended sample.

It should be noted that this procedure, like the human brain, fails for regular grids of points: in fact in this case there would be no bin in the  $\alpha - \beta$  plane containing just one triangle pair. Regular grids of points are typical of

<sup>56</sup>The 2D pattern-recognition is not applied if less than three spectra are detected on the CCD: in such cases, just local solutions would be used. Incidentally, a mask containing just one or two slits can hardly be considered a MOS mask.

<sup>57</sup>Imposing a reading order to the triangle sides eliminates the reflection invariance of the computed quantities.

<sup>58</sup>A preliminary test on set P would ensure that the pattern is not ambiguous, i.e., that isolated points on the  $\alpha - \beta$  plane exists.

<sup>59</sup>In practice, a third dimension is added to the  $\alpha - \beta$  plane, corresponding to the absolute size of the triangles in one of the two input sets.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	117 of 132

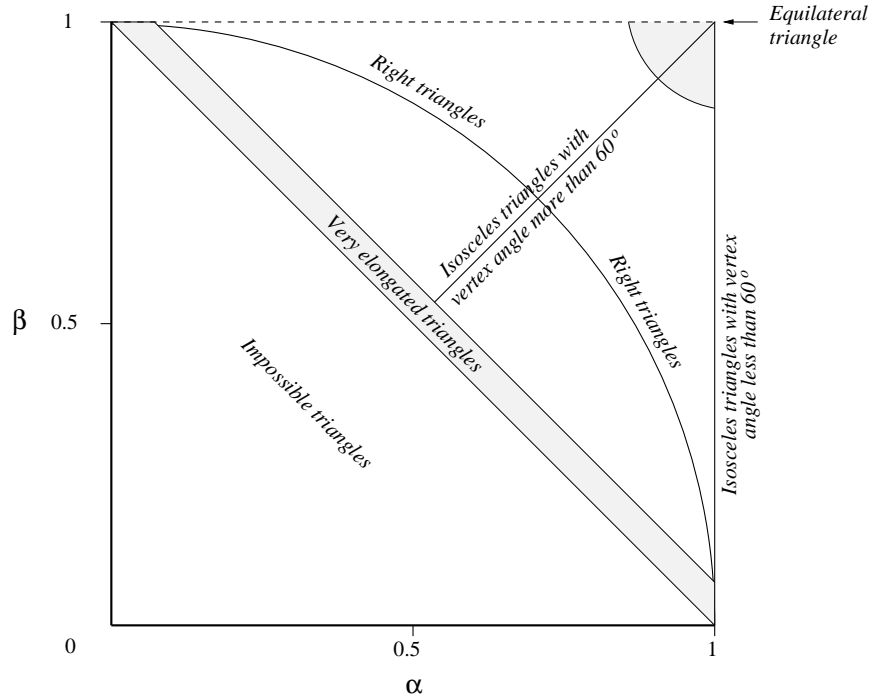


Figure 10.6.5: The  $\alpha - \beta$  plane. The long shaded region indicates very elongated triangles (including the cases of aligned points), while the region about the equilateral triangle includes ambiguous cases that would not lead to a safe identification of points: the triangles contained in those regions are therefore excluded from the analysis (unless they turn out to be the only triangles available). Note that the coordinates are cyclical: the line  $\beta = 1$  (dashed) would include the same triangles described by the line  $\alpha = 1$ .

MOS calibration masks, but such masks always contain at least one asymmetric point, misaligned with the rest of the grid. This single point is sufficient to create a great number of unique triangles, making this procedure work.

A possible drawback of this method lies on the exploding number of triangles at the increase of the points in the pattern. The number of possible triangles that can be drawn from a distribution of  $n$  points is given by

$$N = \binom{n}{3} = \frac{n(n-1)(n-2)}{6}$$

A VIMOS mask may contain up to 200 slits, meaning more than three million triangles to be handled. Even if elongated and ambiguous triangles are excluded from the analysis, they still need to be computed, and the time complexity of this algorithm remains  $O(n^3)$ . For this reason a simplified version of this algorithm has been used in the EFOSC pipeline recipes implementation, where not all possible triangles are considered, but just those triangles defined by nearby slits.

The 2D pattern-recognition algorithm is also applied in the identification of standard stars, in the *efosc\_zeropoint* recipe: in this case the *observed* set,  $D$ , contains the positions (in pixel) of detected stars on a standard star field exposure. Typically hundreds of star positions would be available, but for efficiency reasons only the brightest ones are used for a preliminary identification. The input *observed* positions are therefore opportunely ordered

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	118 of 132

from the brightest to the dimmest star positions. The *pattern* set,  $P$ , is derived from the input standard star catalog. From the WCS defined in the FITS header of the image (which might be inaccurate, sometimes shifted by several pixels if the guide star was misidentified), a subset of stars expected in the field-of-view can be selected from the input catalog: such stars will be stored in the *pattern*, ordered as well by their brightness, and with their RA and Dec coordinates converted into CCD coordinates using again the WCS defined in the FITS header of the image. For an efficient pattern-recognition, the number of constructed triangles is drastically reduced by selecting just the 10 brightest catalog stars, and searching their pattern among the 30 brightest observed stars. From this preliminary identification of a limited number of stars a first rough transformation from *pattern* to *observed* can be determined, and then applied to all the stars in *pattern* to complete the identification of all the standard stars in the observed set.

This 2D pattern-recognition method is successfully applied in the identification of standard stars in the FORS pipeline, as well as for correcting WCS in the WFI pipeline, and as a possible recovery method for echelle instrument instabilities in the X-Shooter pipeline.

#### 10.6.7 Optical distortion model determination

The optical distortion model may be (optionally) obtained by fitting a polynomial transformation to the matching points on the mask and on the CCD planes, as found by the 2D pattern-recognition task (see previous Section). The used polynomial model is described in Section 7.5.

Once the optical distortion model is determined, it is applied to the positions of the slits on the mask plane, improving the accuracy of their computed positions on the CCD.

No optical distortion model can really be defined if there are too few spectra on the CCD: in that case, just a local position of the reference wavelength is used for each individual spectrum, and the slits are left unidentified.

Note that slit identification is not essential to the data reduction, and it is hardly a requirement when very few slits are in use.

#### 10.6.8 Tracing slit spectra edges

The spatial curvature is determined by tracing the slit spectra – typically from flat field and scientific exposures. Flat field spectra are ideal for this operation, because the signal is continuous and with high S/N ratio; on the other hand, it is generally necessary to trace also the scientific spectra, to compensate for possible instrument instabilities. Scientific spectra are generally traceable, because the exposure times are typically long enough to produce a very bright sky spectrum. In case the sky emission is not traceable, then the curvature model derived from the flat field exposures must be used.<sup>60</sup> Currently the pipeline does not support tracing of the scientific spectra.

Tracing spectral edges is not a simple task, because the slit spectra are not always so well detached and isolated from each other, and edges from different spectra may overlap. The only possibility is to try to determine a global trend of the spatial curvature based on the well traceable edges, in order to obtain the curvature also where it cannot be directly measured (see next Section).

<sup>60</sup>Tracing bright point-like object spectra is not a solution, as they are not distorted just by optics, but by atmospheric refraction too.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	119 of 132

### 10.6.9 Spatial curvature model determination

A local spatial curvature model is derived by fitting a low degree polynomial to the traces of one spectral edge. If enough spectra are available, the local curvature model may be superseded by a global description obtained by modeling the coefficients of the local models of all spectra. The used model is described in Section 7.5.

### 10.6.10 Extraction of slit spectra

The extraction of slit spectra consists in reading the spectra following their curvature. The extracted spectra are not wavelength calibrated. This extraction method is only applied to arc lamp or sky spectra before using them for determining the (local) wavelength calibration applying the 1D peak detection and pattern-recognition methods described in Sections 10.6.1 and 10.6.2.

All the spectra are read along the spatial direction (i.e., along the CCD columns), and each column is remapped to a new image where the spatial curvature is eliminated. In other words, the  $x$  coordinate of the rectified image is still the  $x$  coordinate of the CCD.

### 10.6.11 Alignment of the extraction mask to the scientific spectra

A variation of the instrument flexures between the calibration and the scientific exposures would invalidate the extraction mask derived from the calibrations. Also the removal and the insertion of the slit mask may slightly change the absolute positions of the slits on the telescope focal plane with respect to calibrations. Similarly, the grism alignment may also vary.

Flexures, non-reproducible mask positions, grism rotation, temperature changes, and other unpredictable effects, have a complex impact on each of the extraction mask components - i.e., the optical distortion model, the curvature model, and the wavelength calibration.

A practical approach to this problem might be to use the sky slit spectra for deriving a second extraction mask, following exactly the same procedure described in the previous sections – where a catalog of sky-lines would be used instead of a catalog of arc lamp lines. The sky-based extraction mask would be statistically less accurate than the one based on flat fields and arc lamps, but it could still be used to determine a best alignment of the high-quality extraction mask to the scientific observation.

First, the optical distortion models would need to be compared. The transformation matrix between one model and the other can be easily determined, because all CCD positions are already associated to the appropriate mask slit as a by-product of the data processing.

With a similar procedure, the modifications to be applied to spatial curvature and spectral dispersion models can also be derived.

Currently the EFOSC pipeline just derives a correction for the wavelength calibration.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	120 of 132

## A Troubleshooting Guide

In the following sections, a troubleshooting guideline for the EFOSC pipeline spectroscopic recipes is given. It is assumed here that some familiarity with these recipes was already acquired.

See also Sections 9.7.3 and 9.8.3 of this Manual.

### A.1 Checking the results of recipe `efosc_calib`

Things can go wrong. In this Section a number of basic checks are suggested for ensuring that the *efosc\_calib* recipe worked properly. Troubleshooting is given separately, in the next Section, in order to avoid too many textual repetitions: it often happens, in fact, that different problems have the same solution. Three basic checks are described here: spectra localisation, wavelength calibration, and spectral resolution. It is advisable to perform such checks in the given order, because some results make only sense under the assumption that some previous tasks were performed appropriately. For instance, an apparently good wavelength calibration does not imply that the slit spectra were all properly traced.

#### A.1.1 Were all spectra detected and properly traced?

Compare (blink) the *master\_norm\_* and the *master\_screen\_flat\_mos.fits* images. The normalised flat field image can be used as a map showing where the spectra were found and how they were cut out from the CCD, while the master flat image shows where the spectra actually are. A quick visual inspection will immediately expose any badly traced, or even lost, spectrum. This kind of failure may not be so apparent in the *reduced\_lamp\_mos.fits* image, which includes just what has been successfully extracted.

The *curv\_traces\_mos.fits* table enables a closer look at the tracing accuracy. The tracings of the top and bottom edges of the spectrum from slit 4, for instance, are given in the table columns labeled "t4" and "b4", for each CCD pixel along the vertical direction given in column "x". Each tracing may be compared with the fitted model: for instance, the modeling of the tracing "t4" is given in the table column "t4\_mod", together with the fit residuals in column "t4\_res", enabling the generation of plots like those shown in Figure 9.7.6, page 83. In order to reduce the residuals, the degree of the fitting polynomial may be increased (using the configuration parameter "cdegree"): it is however advisable to never use polynomials above the 2nd order, unless the residuals are really not acceptable. In Figure 9.7.6 the residuals are less than a tenth of a pixel, and this is acceptable even if they display a systematic trend that may be easily eliminated by fitting a higher degree polynomial. When systematic trends in the residuals are so small (with respect to the pixel size), they can no longer be considered "physical", but rather an effect of the pixelisation of the edge changing with the position along the CCD, as shown in Figure 9.7.6.

#### A.1.2 Were all spectra properly calibrated in wavelength?

Check the *reduced\_lamp\_mos.fits* image first. This image contains the arc lamp spectra from each slit with all the optical and spectral distortions removed. The spectral lines should all appear perfectly aligned and vertical. Particular attention should be given to lines at the blue and red ends of each spectrum, where the polynomial fit is more sensitive to small variations of the signal. The calibrated slit spectra are vertically ordered as in



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	121 of 132

the original CCD frame. The boundaries between individual slit spectra are generally easy to recognise: both because they are often dotted by the emission lines from nearby spectra on the original CCD frame, and because each slit spectrum may cover different wavelength intervals according to its position within the original CCD frame (see Figure 9.7.3, page 76). The position of each spectrum in the calibrated image is always reported in the table *slit\_location\_mos.fits*, at the columns "position" and "length".

More detailed checks on the quality of the solution can be made by examining other pipeline products. The image *disp\_residuals\_mos.fits* contains the residuals of the wavelength solution for each row of each slit spectrum. This image is mostly padded with zeroes, with the only exception of the pixels where a reference line was detected and identified: those pixels report the value of the corresponding residual (in pixel). This image will in general be viewed applying small cuts (typically between -0.2 and 0.2 pixels): systematic trends in the residuals, along the dispersion direction, would appear as sequences of all-positive (white) followed by all-negative (black) residuals, in a wavy fashion, that could also be viewed by simply plotting a profile at different image rows (see Figure 9.7.2, page 74). Systematic residuals in the wavelength calibration are in general not acceptable, and they may be eliminated by increasing the order of the fitting polynomial.

Another product that can be used for evaluating the quality of the fit is the *disp\_residuals\_table\_mos.fits* table. Here the residuals are reported in a tabulated form for each wavelength in the reference lines catalog, but just for one out of 10 rectified image rows (i.e., one out of 10 solutions). In conjunction with the *delta\_image\_mos.fits* image, plots like the ones in Figure 9.7.1, page 73, can be produced.

Finally, the table *disp\_coeff\_mos.fits* might be examined to check how many arc lamp lines were used (column "nlines") and what is the mean uncertainty of the fitted wavelength calibration solution (column "error"), for each row of each slit spectrum. The model mean uncertainty is given at a 1- $\sigma$  level, and has a statistical meaning only if the fit residuals do not display any systematic trend and have a random (gaussian) distribution around zero. Typically this uncertainty will be of the order of 0.05 pixels, i.e., much smaller than the root-mean-squared residual of the fit, depending on the number of fitted points (a fit based on a large number of points is more accurate than a fit based on few points). It should be anyway kept in mind that the model uncertainty can be much larger than that (up to 1 pixel in the worst cases) at the blue and red ends of the fitted wavelength interval. This is because in the pipeline the wavelength solution is obtained by fitting a polynomial, rather than a physical model of the instrument behaviour.

In the case of long-slit data, if the parameter "wmode" is set to 2 (the default), the wavelength calibration can be much more accurate than that, even at the extremes of the spectral range. The errors reported in *disp\_coeff\_mos.fits* always refer to the single calibrations (each CCD row is calibrated independently), but if "wmode" is set to 2 a global model is fitted to all the reference lines visible on the whole CCD, leading to a calibration accuracy of the order of 0.001 pixels (at least theoretically: systematic errors, e.g., due to physical irregularities of the long slit, are not included in this estimate).

### A.1.3 Is the spectral resolution as expected?

The table *spectra\_resolution\_mos.fits* reports on the mean spectral resolution, defined as  $R = \lambda / \Delta\lambda$  (with  $\Delta\lambda$  determined at half-maximum), which was measured for each reference arc lamp line (see Figure 9.7.5, page 79). The standard deviation from this mean is also given, together with the number of independent determinations of  $R$  in column "nlines".

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	122 of 132

## A.2 Fixing pattern-recognition failures in *efosc\_calib*

In this Section and the following a set of possible solutions to almost any problem met with the *efosc\_calib* recipe is given. It is advisable to try them in the same order as they are listed here. It may be useful to go through this check list even in case the recipe seemed to work well: there might always be room for improvement.

In practice, almost any problem with the pipeline is caused by a failure of the pattern-recognition task. Pattern-recognition is applied to detect the slit spectra on the CCD, assuming that they all will include an illumination pattern similar to the pattern of wavelengths listed in the reference arc lamp line catalog.

**In the case of generic MOS data**, for an immediate visualisation of how successful was the pattern-recognition just rerun the *efosc\_calib* recipe setting the "check" parameter to *true*. This will produce a number of extra (intermediate) products. One of them is the *spectra\_detection\_mos.fits* image, a by-product of the pattern-recognition task, displaying a preliminary wavelength calibration of the CCD. This image has as many rows as the CCD has columns: if at any CCD column (counted from left to right) the line catalog pattern is detected, the spectral signal is wavelength calibrated, resampled at a constant wavelength step, and written to the corresponding row (counted from bottom to top) of the *spectra\_detection\_mos.fits* image. If a row of this image is empty, it is either because the corresponding CCD column doesn't contain any spectrum, or because the pattern-recognition task failed for that column. The check image may simply be rotated clockwise and placed side by side with the original CCD exposure, in order to see if and how frequently a spectral signal was not recognised as such. A few failures (i.e., a few empty rows) are generally acceptable, as they are recovered by interpolation during the final wavelength calibration task. However, a high failure rate is probably the reason why a bad spectral localisation, a bad tracing, a bad final wavelength calibration, were possibly obtained.

**In the case of long-slit data**, for an immediate visualisation of how successful was the pattern-recognition just rerun the *efosc\_calib* recipe setting the "wmode" parameter to 0. This will disable the computation of a global model of the wavelength calibration. The image *reduced\_lamp\_mos.fits* may look a bit noisier than the same image obtained with "wmode" set to 2, and some of its rows may contain no signal. The *reduced\_lamp\_mos.fits* image covers an interval of CCD rows beginning with the first and ending with the last row where a local solution was found. Within this interval, if at any CCD row the line catalog pattern is detected, the spectral signal is wavelength calibrated, resampled at a constant wavelength step, and written to the corresponding row of the *reduced\_lamp\_mos.fits* image. If a row of this image is empty it is because the pattern-recognition task failed for that row. A few failures (i.e., a few empty rows) are generally acceptable, as they are easily recovered by the global model interpolation. However, a high failure rate is probably the reason why a bad (global) wavelength calibration was possibly obtained.

What can make the pattern-recognition task fail? One or more of the following causes may be determined:

### A.2.1 Some arc lamp reference lines are missing

It is possible that the searched pattern is simply not present in the data: for instance, the Neon lamp was off, so only Argon + Helium lines are present.

*Solution:* Change line catalog accordingly.

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	123 of 132

### A.2.2 Some arc lamp reference lines are very faint

It is possible that the exposure time for the arc lamp frame is too short, or one of the lamps got too faint with age. If some of the reference lines listed in the catalog do not peak above a given threshold, they are not used by the pattern-matching task.

*Solution:* Specify a lower value for the "peakdetection" parameter. Alternatively, if this gets too close to the noise level, remove the faint lines from the reference line catalog.

### A.2.3 The reference lines in the arc lamp exposure are very broad

If very wide slits are used, the reference lines would become accordingly wider (and would display a box-like, flat-top profile). The calibration recipe can handle this in case of well isolated lines, but if nearby lines blend together it is impossible to safely determine their positions.

*Solution:* None. These spectra cannot be calibrated.

### A.2.4 The spectral dispersion is not what expected

The actual mean spectral dispersion is significantly higher (or lower) than expected. The first-guess spectral dispersion is specified via the parameter "dispersion", and is tabulated for each grism in the EFOSC2 User's Manual [10], or in the grism tables which are included in the distributed EFOSC pipeline package. In general the pattern-recognition algorithm is quite robust against changes of the spectral dispersion (up to 20% from expectation). Still it may happen that a small change of the spectral dispersion (perhaps caused by a large temperature variation) may cause the wavelength calibration to fail.

*Solution:* Try different values of the "dispersion" parameter around the expected (default) value, and select the one producing the lowest failure rate of the pattern-recognition task.

### A.2.5 There are spectra at very large offsets

The CCD may include spectra at such large  $x$  offsets that only part (red or blue) of their full wavelength range is really included in the CCD. If the line catalog contains too few reference lines in this region (say, less than 5), they might not be enough to define an unambiguous pattern to detect.

*Solution:* Add extra reference lines to the line catalog, for a more complete coverage of the bluest/reddest parts of the complete spectral range. If there are no extra lines to be used as a reference, the truncated spectra will then be definitely lost.

## A.3 Fixing other possible failures in efosc\_calib

If the pattern-recognition seems to have worked properly, the reason of a *efosc\_calib* recipe failure can be found elsewhere:

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	124 of 132

### A.3.1 The spectra are too tightly packed

If slits are too close to each others, there is a risk that (some of) the spectra would not be properly traced, or not traced at all, on the flat field frames. As a default, the *efosc\_calib* recipe tries to recover untraceable edges by interpolating a global curvature model based on other traceable edges (if they are available). Using this global description of the spectral curvature helps to extract also those spectra whose edges cannot be traced. In some cases however the recipe may find and accept a bad tracing as if it were good, producing a bad global curvature model, and therefore a bad spectral extraction.

*Solution:* Setting the parameter "cmode" to zero will suppress the usage of the global curvature model. In this case the recovery strategy of lost spectral edges will consist in replicating the trace of the other available spectral edge (opportunely shifted) of the same slit spectrum. This may improve the results in some cases: however, if a tracing is missing for both edges of a slit spectrum, the spectrum will not be extracted.

### A.3.2 The wavelength calibration residuals display systematic trends

Especially if the extracted spectral range is very large, the fitting polynomial may be incapable to replicate the physical relation between pixel and wavelength. In this case, any estimate of the statistical error (such as the fit uncertainties listed in *disp\_coeff\_mos.fits*) will become meaningless.

*Solution:* Increase the degree of the fitting polynomial, using the parameter "wdegree". Beware that this may introduce overfitting, especially at the red and blue ends of the spectra (i.e., the polynomial is so poorly constrained in those regions where few points are available, that it also fits their position uncertainty, incorporating this noise into the solution: the corresponding residuals may therefore look very small, and yet the calibrated spectra will appear to be badly calibrated; an extreme case of overfitting is, for instance, fitting 4 points with a 3rd degree polynomial: the residuals will be exactly zero, and yet the obtained model will be highly inaccurate). For this reason, while applying this solution it may be also appropriate to set the parameter "wmode" to 2 (for long-slit data), or the parameter "wmosmode" to 1 or 2 (for generic MOS data).

### A.3.3 The calibrated spectra look "noisy" at their ends

This problem is symmetric to the previous one: the fit residuals may look very small, and yet the calibrated spectra will appear to be badly calibrated at their blue and red ends. This is the effect of model overfitting.

*Solution:* Decrease the degree of the fitting polynomial, using the parameter "wdegree". Beware that this may introduce systematic fit residuals.

### A.3.4 The calibrated long-slit spectrum looks distorted

If the global wavelength calibration model is bad, it is either because some of the local solutions are bad, or because there are too few local solutions available for global modeling.

*Solution:* Rerun the recipe with the parameter "wmode" set to 0, and change opportunely the recipe configuration (especially the parameter "dispersion"), trying to maximise the number of obtained local solutions and

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	125 of 132

to get more uniform results in the *reduced\_lamp\_mos.fits* image. Finally run the recipe with the new found configuration, but setting the parameter "wmode" back to 2.

### A.3.5 The flat field is not properly normalised

The master flat field is normalised by dividing it by a smoothed version of itself. For various reasons the result may be judged unsatisfactory.

*Solution:* If you are dealing with MOS data, change the smoothing box sizes using the parameters "dradius" and "sradius". Alternatively, instead of the default median smoothing, a polynomial may be used to fit the large scale trend: the degree of the fitting polynomial should be specified via the "ddegree" parameter.

*Solution:* If you are dealing with long-slit data, change the "sdegree" parameter, indicating the degree of the polynomial fitting the large scale illumination trend along the spatial direction. Alternatively, instead of the default polynomial fitting a median smoothing may be applied: "sdegree" should be set to -1, so that the smoothing box sizes can be specified with the parameters "dradius" and "sradius".

### A.3.6 Valid reference lines are rejected

Sometimes the peak detection algorithm may return inaccurate positions of the detected reference arc lamp lines. Outliers are automatically rejected by the fitting algorithm, but if those lines were properly identified, not rejecting their positions may really improve the overall accuracy of the wavelength calibration.

*Solution:* Increase the value of the "wreject" parameter. Extreme care should be used here: a tolerant line identification may provide an apparently good fit, but if this is based on misidentified lines the calibration would include unknown systematic errors.

## A.4 Checking the results of recipes efosc\_science

In this Section a number of basic checks are suggested for ensuring that the recipe *efosc\_science* worked properly. Troubleshooting is given separately, in the next Section, in order to avoid too many textual repetitions: it often happens, in fact, that different problems have the same solution. Four basic checks are described here: wavelength calibration, sky subtraction, object detection, and object extraction. It is advisable to perform such checks in the given order, because some results make only sense under the assumption that some previous tasks were performed appropriately. For instance, an apparently good sky subtraction does not imply that the slit spectra were all properly wavelength calibrated.

### A.4.1 Were all spectra properly wavelength calibrated?

The wavelength calibration based on calibration lamps, performed at day-time, may not be appropriate for an accurate calibration of the scientific spectra: systematic differences due to instrumentaleffects, such as flexures, may intervene in the meantime.

To overcome this, the day calibration may be upgraded by testing it against the observed positions of the sky lines in the scientific slit spectra. The alignment of the input distortion models to the true sky lines positions is

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	126 of 132

controlled by the parameter "skyalign", that as a default is set to 0 (i.e., the sky lines correction will be a median offset).

In the case of long-slit data the sky alignment can be quite accurate, and therefore it would be advisable to always apply it, even in the case of very small corrections. The magnitude and the accuracy of the correction can be examined in the `sky_shifts_long_sci_mos.fits` table. This table is quite different from the `sky_shifts_slit_sci_mos.fits` table produced in the case of MOS data reduction.

The overall quality of the wavelength calibration (whether a sky line alignment was applied or not) can be examined in the `mapped_all_sci_mos.fits` image. This image contains the scientific spectrum after resampling at a constant wavelength step. The visible sky lines should all appear perfectly aligned and vertical.

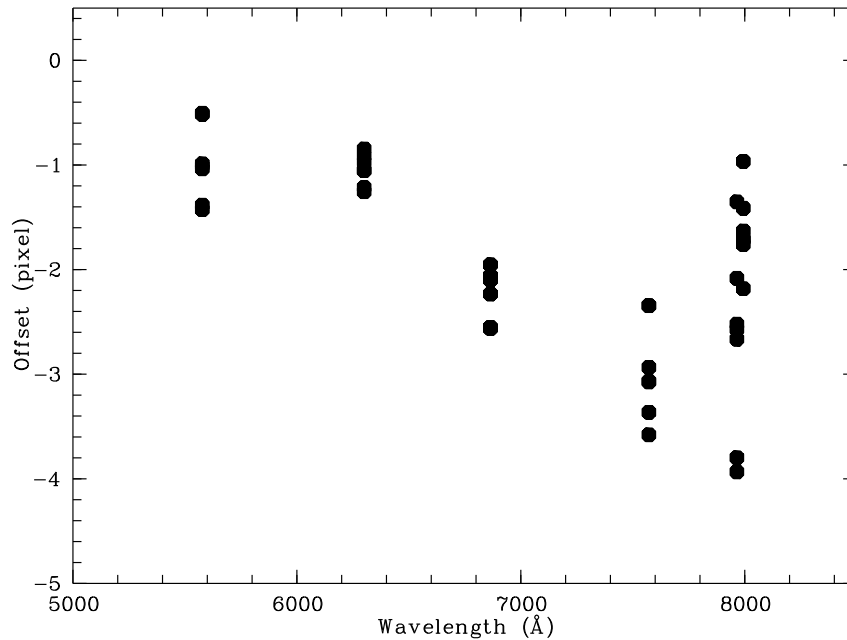


Figure A.4.1: *Systematic sky line offsets (in pixel) from day-calibration expectation, observed in a scientific exposure with grism #1. The offsets from all slits are plotted. All offsets are systematically negative, and therefore a sky alignment of the wavelength solution is due. It can also be seen that the wavelength offsets depend on the wavelength: typically the spectral dispersion of the EFOSC2 spectrograph depends on the temperature, which changes between day (calibration) and night (observation). In general it would be appropriate to set the parameter "skyalign" to 1. In this particular observation it may also be appropriate excluding the line at 7993 Å from the fit.*

In the case of MOS data the quality of the alignment may be quite poor. It is possible, however, that an alignment of the distortion models was unnecessary: if this were the case, it would be better to avoid it entirely (any extra manipulation increases the statistical uncertainties on the final product). In order to decide whether a sky alignment is necessary or not, the `sky_shifts_slit_sci_mos.fits` table can be examined. This table has a column labeled "wave", listing the wavelengths of all the reference sky lines found within the extracted spectral interval, and a number of columns labeled "offset\_id", listing the median offset in pixels for each sky line from its expected position, for the slit identified by "id" (see Figure A.4.1). *Beware:* the listed offsets are not the



ESO	EFOSC2 Pipeline User Manual	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	127 of 132

residuals of the final sky line alignment, but really the comparison of the sky line positions against expectations from the input distortion models. In case the sky line offsets are compatible with zero, the sky line alignment is really unnecessary, and the *efosc\_science* recipe may be run again setting the "skyalign" parameter to  $-1$  (i.e., the sky lines correction will be disabled). This is not strictly necessary, but it is often wise to keep data manipulation to a minimum. On the other hand, observing systematic offsets would confirm that an alignment of the distortion model to the true sky lines positions was in order, and there would be no need to reprocess the data. In case the offset appears to depend on the wavelength, it may be appropriate to set the parameter "skyalign" to 1.

The overall quality of the wavelength calibration (whether a sky line alignment was applied or not) can be examined in the *mapped\_all\_sci\_mos.fits* image. This image contains the scientific spectra from each slit after removing the optical and spectral distortions. The visible sky lines should all appear perfectly aligned and vertical. The position of each spectrum in the calibrated image is listed in the table *object\_table\_sci\_mos.fits*, at the columns "position" and "length".

A further check on the quality of the solution can be made by examining the *disp\_coeff\_sci\_mos.fits* table. This table is only produced in case a sky line alignment was performed. Column "nlines" reports how many sky lines were used for the distortion model correction, while the "error" column reports the mean uncertainty of the new wavelength calibration solution for each slit spectrum row. The model uncertainty is given at a  $1-\sigma$  level, and is computed as the quadratic mean of the input model accuracy and the sky line correction accuracy. Typically this uncertainty will be of the order of 0.1 pixel, i.e., much smaller than the root-mean-squared residual of the lamp calibration and of the sky line correction, depending on the number of fitted points. It should be anyway kept in mind that the model uncertainty can be much larger than that (up to 1 pixel in the worst cases) at the blue and red ends of the fitted wavelength interval. This is because in the pipeline the wavelength solution is obtained by fitting a polynomial, rather than a physical model of the instrument behaviour.

#### A.4.2 Is the sky background properly subtracted?

A quick check on sky subtraction can be made by examining the sky subtracted frames, *mapped\_sci\_mos.fits* and *unmapped\_sci\_mos.fits* (if available, depending on how the recipe was run). The spectra should have a generally smooth look, and will only appear to be noisier in those regions where bright sky lines were subtracted.

In the case of long-slit data, the sky subtraction performed by the pipeline is not really accurate. The "skylocal" method in this case is equivalent to the "skymedian" method: the sky subtraction is always performed *after* data resampling at constant wavelength step. This problem would be fixed in the next pipeline releases, but in the meantime it is suggested to use the sky subtraction applied to long-slits just for quick-look, and not for scientific purposes.

The best way to ensure that the sky was subtracted optimally, at least at the positions of the objects to extract, is to check that the residual noise is compatible with the statistical error associated to the extracted object spectra. The extracted spectra are contained in the *reduced\_sci\_mos.fits* image (one extracted spectrum for each row). Their error spectra (at a  $1-\sigma$  level) are contained in the *reduced\_error\_sci\_mos.fits* image. The regions of the extracted spectra corresponding to a (bright) sky line will include a few noisier points, whose deviation from the spectral continuum should (almost) never pass the  $3-\sigma$  deviation. If this condition is fulfilled, the sky subtraction is probably as good as it can get.

Note that the subtracted sky can be viewed in the images *mapped\_* and *unmapped\_sky\_sci\_mos.fits*. More

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	128 of 132

useful is perhaps the image containing the extracted sky spectra, *reduced\_sky\_sci\_mos.fits*: such spectra are extracted applying to the modeled slit sky spectra exactly the same weights that were used in the object extraction.

#### A.4.3 Were all objects detected?

The answer to this question is almost always "no". The pipeline, after removing the instrument signature and the sky background from each slit spectrum, will run an object detection algorithm in order to find all the objects which need to be extracted. There will always be a detection threshold beyond which an object will not be significant enough for selection – no matter what detection algorithm is applied. Using more tolerant detection criteria would not eliminate this threshold effect, and may increase the number of false detections to the point of making the object detection task impractical.

The list of detected objects can be found in the *object\_table\_sci\_mos.fits* table.

#### A.4.4 Were all the detected objects properly extracted?

As a default the *efosc\_science* recipe would apply an optimal extraction algorithm to each detected object spectrum. This algorithm is only appropriate for point-like objects emitting over (almost) all the extracted wavelength interval, while it is not appropriate for extended objects, and it is ineffective for objects having a spectrum only consisting of emission lines with no continuum.

The statistical noise on the extracted object spectra should in principle decrease if the spectra are optimally extracted. In order to check the improvement of the noise level, it is easy to compare the *reduced\_error\_sci\_mos.fits* images obtained by running the recipe with and without optimal extraction. A 30% increase of the signal-to-noise ratio can be obtained for faint-objects (background-noise limited), while there would be little or no improvement for brighter sources. The photometric accuracy of the optimal extraction can be checked by simply computing the ratio (or the difference) of the *reduced\_sci\_mos.fits* images obtained once with the standard and once with the optimal extraction: the result should be a flat image, displaying no trends or systematic deviations from 1 (or 0).

### A.5 Fixing failures in *efosc\_science*

In this Section a set of possible solutions to the most common problems with the *efosc\_science* recipe is given. It is advisable to try them in the same order as they are listed here. It may be useful to go through this check list even in case the recipe seemed to work well: there might always be room for improvement.

#### A.5.1 The wavelength calibration is bad

Aligning the wavelength calibration to the position of the observed sky lines may be inaccurate, especially if very few reference lines are used. If a sky line alignment is really required (see previous Section), then action needs to be taken to solve this problem.

*Solution:* If very few reference sky lines are used, supplying a sky line catalog including more lines (even if weak and/or blended) may help a lot.



<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	129 of 132

*Solution:* If the wavelength calibration appears to be bad only at the blue and/or red ends of the spectra, go back to the *efosc\_calib* recipe to obtain a more stable wavelength calibration in those regions (e.g., either by adding new reference arc lamp lines, or by decreasing the fitting polynomial degree).

### **A.5.2 The sky alignment of the wavelength solution failed**

In case a blue grism is used, or if a spectrum has a large offset toward the red, no sky lines may be visible within the observed spectral range.

*Solution:* None. It is however possible to modify the columns of coefficients in the input *disp\_coeff\_mos.fits* table, if the correction can be evaluated in some other way. For instance, the solution can be shifted by adding a constant value (in pixel) to column "c0".

### **A.5.3 The sky subtraction failed for resolved sources**

In case of extended objects filling most or all of the slit, the evaluation of the sky may be strongly biased by the inclusion of signal that actually belongs to the object to extract. Subtracting this contaminated background would actually destroy the object spectrum.

*Solution:* The default sky subtraction method (parameter "skylocal") performs very well for point-like sources where plenty of sky is directly observable within the slit. An alternative method is made available for extended objects (parameter "skyglobal"). Setting "skylocal" to *false* and "skyglobal" to *true* would subtract from all spectra a supersampled model of the median sky spectrum observed in all slits. This method would perform optimally only in case the spectral resolution were the same all over the detector: in practice, this method is always less accurate than the "skylocal" method. But even if it is less accurate, this method remains the extended sources best friend. It is always possible to process the scientific exposures in both ways, one for processing point-like sources and the other for processing spatially resolved sources.

### **A.5.4 The sky subtraction failed for curved or tilted slits**

Obvious residuals related to the sky subtraction are visible on the extracted slit spectra.

*Solution:* Change sky subtraction method: set "skylocal" to *false* and "skymedian" to *true*. The difference between the two methods is that "skylocal" would subtract the sky *before*, and "skymedian" *after* the rectification of the spectral data. The second method performs very poorly in comparison to the first, but in the case of curved or slanted slits there is at the moment no other choice than using it. This problem will be fixed in the next pipeline releases.

### **A.5.5 Cosmic rays are not removed**

As a default the *efosc\_science* recipe does not remove cosmic rays hits, leaving them on the sky-subtracted slit spectra: if the optimal spectral extraction is applied, most of the cosemics are removed anyway from the extracted spectra. Optimal extraction is however not always applicable, especially in the case of resolved sources.

<b>ESO</b>	<b>EFOOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	130 of 132

*Solution:* Set the "cosmics" parameter to *true*. This will apply a cosmics removal algorithm to the sky subtracted spectra. The removed cosmic rays hits will be included in the (modeled) sky images, *mapped\_sky\_sci\_mos.fits* and *unmapped\_sky\_sci\_mos.fits*.

#### **A.5.6 The sampling of the remapped scientific spectra is poor**

When the slit spectra are rectified and wavelength calibrated, they are remapped undistorted to images such as *mapped\_sky\_sci\_mos.fits* or *mapped\_sci\_mos.fits*. This remapping may be judged to undersample the signal along the dispersion direction.

*Solution:* Change the value of the "dispersion" parameter. This parameter doesn't need to be identical to the one used in the *efosc\_calib* recipe.

It should be noted, however, that making the sampling step smaller will not really increase the information contained in the remapped spectra. As a matter of fact, even maintaining a resampling step close to the original CCD pixel size, the remapped pixel values would still be obtained by interpolating the values from a number of original pixels that are close to the interpolation point: nearby interpolation points would surely share common information, and this is what introduces correlated noise in the result. Decreasing the resampling step would just increase this effect. In general, working on remapped spectra means to accept that the spectral signal was heavily manipulated, and it is for this very reason that the *efosc\_science* recipe also produces reduced – but still unmapped – spectra, as in the *unmapped\_sci\_mos.fits* image.

#### **A.5.7 The extracted spectra are normalised in time**

The default behaviour of this recipe is to normalise the results to the unit exposure time.

*Solution:* Set the parameter "time\_normalise" to *false*.

#### **A.5.8 There are often spurious objects detected at the slit edges**

As a default the *efosc\_science* recipe excludes objects that are detected within 3 pixels from the slit ends. This might not be enough in some cases.

*Solution:* Increase the value of the "slit\_margin" parameter.

#### **A.5.9 Some "obvious" objects are not detected**

Examining the *mapped\_sci\_mos.fits* and *unmapped\_sci\_mos.fits* images it may appear that some clearly visible object spectra are not detected (let alone extracted) by the recipe.

*Solution:* Setting "cosmics" to *true* (cleaning cosmic rays hits) may help.

*Solution:* Try different set of values for the parameters "ext\_radius" and "cont\_radius".

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	131 of 132

## **B Installation**

See <http://www.eso.org/pipelines/efosc/efosc-pipe-recipes.html>

<b>ESO</b>	<b>EFOSC2 Pipeline User Manual</b>	Doc:	VLT-MAN-ESO-19520-5222
		Issue:	Issue 1.1
		Date:	Date 2011-02-02
		Page:	132 of 132

## C Abbreviations and acronyms

CPL	Common Pipeline Library
DFS	Data Flow System
DMO	Data Management and Operation Division
DO	Data Organiser
DPD	Data Products Department
DRS	Data Reduction System
ESO	European Southern Observatory
FITS	Flexible Image Transport System
FOV	Field Of View
FPN	Fixed Patter Noise
GUI	Graphical User Interface
IPOL	Imaging polarimetry
IWS	Instrument Work Station
MOS	Multi Object Spectroscopy
PAF	VLT PArAmeter File
PSO	Paranal La Silla Site Operations
PWS	Pipeline Work Station
QC	Quality Control
RON	Read Out Noise
SDD	Software Development Division
SOF	Set Of Frames
UT	Unit Telescope
VLT	Very Large Telescope
WCS	World Coordinate System